U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

NHTSA
www.nhtsa.gov

DOT HS 811 764

May 2013

Tire Oven-Aging Test and Roadwheel Testing to Failure: Tire Aging Phase 3 Research

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 811 764		

4. Title and Subtitle	5. Report Date
Tire Oven-Aging Test and Roadwheel Testing to Failure: Tire Aging Phase 3 Research	May 2013
	6. Performing Organization Code
7. Author(s) Larry R. Evans[1], James D. MacIsaac Jr.[2] [1]Transportation Research Center Inc., [2]National Highway Traffic Safety Administration	8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration Vehicle Research and Test Center P.O. Box B-37 10820 State Route 347 East Liberty, OH 43319-0337	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTNH22-02-D-08062, DTNH22-03-D-08660, DTNH22-07-D-00060
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code NHTSA/NVS-312

15. Supplementary Notes

Project support and testing services provided by the Transportation Research Center Inc., Smithers Scientific Services, Inc., Standards Testing Laboratories, Inc. and Akron Rubber Development Lab

16. Abstract

As a result of the TREAD Act, NHTSA initiated a project to develop a laboratory-based accelerated service life test for light vehicle tires. Phase 1 of this project explored the degradation of tire material properties and roadwheel durability performance during years of service in Phoenix, Arizona. Phase 2 of the project focused on developing an accelerated laboratory-based tire test to simulate service aging. The most effective aging method evaluated in Phase 2 was to inflate a new tire with an oxygen-enriched gas and subject it to elevated oven temperatures for several weeks in order to accelerate the thermo-oxidative aging process that normally occurs during service. The structural integrity of the tires in Phase 2 was evaluated using a stepped-up-load roadwheel test, which showed a reduced time to failure for oven aged tires as compared to new tires of the same models. The results of the first two test phases were used to design a prototype laboratory oven aging and roadwheel test sequence that was evaluated on twenty light vehicle tire models in this phase of the project (Phase 3).

In Phase 3, the material properties and stepped-up-load roadwheel performance of new tires of each model were evaluated as the baseline condition. Other new tires of these models were inflated with oxygen-enriched gas and exposed to a constant temperature of 60º or 65º C in an air-circulating oven for multiple weeks, with a subset of tires subjected to a pre-oven 23-hour roadwheel break-in at 80 km/h. After oven exposure, the material properties and roadwheel durability of the tires were compared to new tire properties. The results of the material properties analysis indicated that oven aging produced thermo-oxidative aging effects that were qualitatively similar to those found in tires after service in Phoenix, Arizona. In roadwheel testing, only one of the 41 (2.5%) new, un-aged tires failed prior to 34 hours in the stepped-up-load test, which is equivalent to the completion of the final load step of the FMVSS No. 571.139 Endurance test. However, after oven aging, 49% of passenger tires and 76% of light truck tires failed prior to 34 hours. An oven test temperature of 65° C was found to be as effective as 60° C in replicating the material properties and roadwheel performance of tires retrieved from service, with the 65° C temperature achieving these results in fewer weeks and at a lower cost. Shorter periods of oven aging and/or a shorter roadwheel break-in would result in fewer tires failing to exceed the 34-hour FMVSS No. 571.139 Endurance test requirement.

17. Key Words	18. Distribution Statement
Tire, tire aging, tire safety, Phoenix, FMVSS No. 139, TREAD Act, accelerated service life, tire durability, roadwheel oven aging	Document is available to the public from the National Technical Information Service www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	90	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Approximate Conversions to Metric Measures				
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	30	centimeters	cm
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Celsius) - 32°C	Celsius	°C

Approximate Conversions to English Measures				
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
km^2	square kilometers	0.4	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

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EXECUTIVE SUMMARY

In response to the TREAD Act of November 1, 2000, NHTSA launched a test development program leading to FMVSS No. 571.139, "*New pneumatic radial tires for light vehicles*," herein referred to as §571.139. Three methods for testing tire durability were evaluated for §571.139 and the data showed a need for more test development, specifically in the area of service-related tire degradation.

Phase 1 of this program sought to better understand service related tire degradation. On-road and full-size spare tires of six different models were retrieved from vehicles in Phoenix, Arizona after varying amounts of service. Changes in properties from those of new tires occurred due to thermo-oxidative aging and cyclic fatigue. These changes could lead to subsequent risks with overloading/underinflation and by using tires near the top end of their speed rating.

Phase 2 looked to develop an accelerated laboratory test to simulate tire aging. Three methods of laboratory tire aging were evaluated using new tires of the same six models studied in Phase 1. Two methods supplied by the tire industry (Michelin and Continental) consisted of aging and durability tests on a 1.707 m indoor roadwheel and a third method, from Ford[12], who recommended heating tires inflated with a mixture of $50\%N_2/50\%O_2$ in an oven in an oven, and tested them on an indoor roadwheel as in the tire industry tests. The properties of the belt rubber compounds for new tires were compared to those of the same models after laboratory aging by each of the three methods. Using results from Phase 1 service aging in Phoenix as the baseline, oven aging proved the most effective of the three laboratory aging methods evaluated.

Phase 3 compared properties for 10 passenger vehicle and 6 light truck tire models that had been laboratory aged to the properties of new tires of the same model. The residual integrity of 12 passenger and 8 light truck tires was measured using a stepped up load test to structural failure after aging for 7 weeks at 60°C, or 5 weeks at 65°C. The effect of a 23-hour break-in cycle on a 1.707 m roadwheel at 80 km/h prior to oven aging was also investigated. All tires tested in Phase 3 were manufactured prior to the adoption of the updated §571.139 standard and therefore were not required to meet the more severe performance requirements of §571.139.

With no service-aged tires of the Phase 3 models available for comparison, values of the measured properties for the aged tires are shown as a percentage of the same properties for new tires of the same model. Changes in the physical properties of all tires tested were similar to the results from Phase 1 and 2: Increases in indentation modulus and decreases in tensile strength and ultimate elongation for oven aged tires were similar to those of service aged tires. For certain tires, achieving the modulus found during service requires a roadwheel break-in cycle prior to oven aging.

Testing using the §571.139 roadwheel test protocol on tires oven aged for 7 weeks at 60°C or 5 weeks at 65°C (calculated to be equivalent to 3.5 to 4 years of Phoenix service) produced failures in a significantly shorter time than that of new tires. Prior to aging only 1 of the 41 tires (2.5%) failed prior to the completion of the 100% load step of the FMVSS No. 139 Endurance test method. After aging 49% of passenger tires and 76% of light truck tires failed prior to the completion of the final 100% load step.

At failure times of less than 34 hours for 49% of the tires, the load on the tire was equal to or less than the rated load of the tire, so the stresses on tire components could have been experienced in

normal service conditions. Approximately two thirds of these failures occurred in the belt area and 22% in the shoulder area. Thirty-five of 46 aged light truck tires (76%) failed in less than 34 hours. Approximately 32% of these failures occurred in the belt area and 10% in the shoulder area. Nine light truck tires (19%) failed by sidewall or innerliner separation during the oven aging process, prior to testing on a roadwheel.

Analysis of the work-to-failure during the stepped-up-load roadwheel had been shown to correlate well to tire service in Phoenix, Arizona. Measurement of average work to failure of the oven aged tires showed a general correlation to some models in Phoenix service. The 20 models of tires studied in this phase all showed a reduction in average work to failure after oven aging. However, there was no clear relationship between average failure times of new tires and tires of the same model after oven aging. The oven aging and roadwheel tests methods evaluated in Phase 3 proved effective in achieving the goal of the project to develop an accelerated service life test for tires that could evaluate the risk of failure at a period later in the life than new-tire tests. An oven test temperature of 65°C was found to be as effective as 60°C in replicating the material properties and roadwheel performance of tires retrieved from service in Phoenix, with the 65°C temperature achieving these results in fewer weeks.

1.0 INTRODUCTION

On September 12, 2000, the U.S. Senate Committee on Commerce, Science, and Transportation conducted a hearing on the recall of 14.4 million Firestone Radial ATX, Radial ATX II, and Wilderness AT tires on specific models of Ford, Mercury, and Mazda light trucks and sport utility vehicles. During these hearings, members of Congress expressed concern that the current Federal Motor Vehicle Safety Standards (FMVSS) do not evaluate how well tires perform when significantly underinflated or after being subjected to environmental variables, such as heat, which accelerate aging.(1) As a result of the committee's actions, the Transportation Recall, Enhancement, Accountability, and Documentation ("TREAD") Act [H.R. 5164, Pub. L. No. 106-414] was enacted on November 1, 2000. Section 10 of the TREAD Act contained provisions mandating the National Highway Traffic Safety Administration (NHTSA) to "revise and update" the passenger car and light truck tire safety standards. The legislation did not mandate specific test requirements. During the consideration and enactment of the TREAD Act, Members of Congress placed particular emphasis on improving the ability of tires to withstand the effects of factors such as heat build-up, low inflation, and aging (i.e., service-related degradation). With regards to aging, the agency was asked to consider the feasibility of requiring a "tire aging test" (i.e., accelerated service life test for tires) to evaluate the risk of failure at a period later in the life of a tire than the current regulation, which only evaluates new tires.

In response to the TREAD Act the agency examined the effectiveness of the current passenger vehicle tire safety standards, which had not been substantially revised since their issuance in 1967, and determined the following:

> "While the durability and performance of tires have improved, the conditions under which tires are operated have become more rigorous. Higher speeds, greater loads, extended lifetimes of tires, longer duration of travel and shifting demographics of vehicle sales have all contributed to much greater stresses and strains being placed upon today's radial tires than those endured by earlier generation radial tires. The characteristics of a radial tire construction in conjunction with present usage and purchasing patterns render the existing required minimum performance levels in the high-speed test, endurance test, strength test, and bead-unseating test ineffective in differentiating among today's radial tires with respect to these aspects of performance."(2)

NHTSA conducted tire safety research in support of what would become the new FMVSS No. 571.139[i], "*New pneumatic radial tires for light vehicles,*" which is herein referred to as §571.139.

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[i] Previously, passenger tires were regulated by the FMVSS No. 571.109 ("Passenger car tires") and light truck tires under the separate FMVSS No. 571.119 ("Tires for vehicles other than passenger car"). The Standard No. 119 had less severe test conditions than the FMVSS 109 and did not include a high speed or bead unseat test for tires. Standard No. 139 unifies regulation of the majority of passenger and light truck tire designs for vehicles with a gross vehicle weight rating of 10,000 pounds or less. This new standard became mandatory on September 1, 2007 for non-snow tire designs and becomes mandatory on September 1, 2008 for designated snow tire designs. Optional compliance was permitted before those dates.

Agency researchers conducted comprehensive literature reviews and had numerous consultations with industry regarding long-term effects of service on radial tire durability. The agency concluded that while most tire manufacturers conduct some form of accelerated service life testing on their tires (“tire aging tests”), their approaches varied widely and a single industry-wide recommended practice did not exist. As part of the §571.139 development research, the agency evaluated multiple laboratory-based accelerated service life tests for tires that were based on either industry submissions or previous agency test experience. In the March 5, 2002 Notice of Proposed Rulemaking (NPRM) section related to tire aging for §571.139 (67 FR 10050), the agency proposed three alternative tests that could be used to evaluate a tire's long-term durability. These approaches were: 1) 24-hours of roadwheel conditioning followed by an adhesion (peel strength) test between the belts; 2) an extended duration roadwheel endurance test with oxygen rich inflation gas; and 3) an oven aging conditioning period followed by a roadwheel endurance test. However, based on the results of an initial evaluation, as well as comments and data from industry, the agency deferred action on the proposal to add an aging test to the new §571.139 until further research was conducted. To conduct this further research, the agency initiated its NHTSA Tire Aging Test Development Project in late 2002.

Phase 1 of the NHTSA Tire Aging Test Development Project analyzed six different tire models collected from service on privately owned vehicles in the Phoenix, Arizona metropolitan area during the spring of 2003. This study was conducted to provide a better understanding of service-related tire degradation and to serve as the “real-world” baseline for laboratory-based accelerated service life test for tires (a “tire aging test”). As part of the Phase 1 effort, the performance of 109 tires retrieved from service in Phoenix, Arizona of varying age and mileage were compared to 45 new tires of the same type and model in one of two laboratory roadwheel tests. Analysis of this data showed that peel adhesion decreases systematically as the tires accumulated mileage time in service in Phoenix. The actual peel adhesion value is a complex function of the thickness of the rubber layer between the belts and the physical properties of the rubber. All new tires and most aged tires failed cohesively in the rubber layer but the intrinsic interfacial adhesion was unknown. The agency rejected peel adhesion as a primary method of evaluating an aged tire’s durability.(3)

The physical and chemical properties of the rubber compound between the belts, known as the skim and wedge compounds, changed in a manner consistent with the mechanism of thermo-oxidative aging. Specifically, the level of fixed oxygen (that is the oxygen reacted with the rubber compound) in the rubber compound between the belts systematically increased as the tires were in service in Phoenix.(4) The hardness and modulus of the rubber compound between the belts changed systematically as the service in Phoenix increased.(3) For five of the tire types, the hardness increased with service time. For the other, hardness and modulus decreased, shown to be an effect of the reinforcing resin used in this rubber compound.(5)

The ultimate elongation to break of the rubber compounds for all tires was significantly reduced as the service time of the tire in Phoenix increased. The tensile strength tended to reduce and the modulus tended to increase, although the trends were not statistically significant for all tires.(3)

The crosslink density systematically increased as the service in Phoenix increased. A small subset of tires tested for distribution of crosslinks showed systematic changes in the crosslink density as the service life in Phoenix increased. Strong crosslinks increased while weak crosslinks decreased, with the effect on intermediate crosslinks being indeterminate.(6)

Ahagon[9] et al. have shown several types of aging taking place in rubber compounds depending on the temperature and available oxygen.[9],[10] The aging of the Phoenix tires corresponded to aerobic thermo-oxidative aging, as shown by the slope of the log(extension ratio at break) versus log(modulus at 100%, MPA) plots.[5]

Phase 2 focused on developing an accelerated, laboratory-based tire test that simulates real world tire aging and evaluates the remaining structural durability of the aged tires. The six tire models previously evaluated after long-term service in Phoenix, AZ were evaluated using three candidate methods of laboratory aging:

1. The Long Term Durability Endurance Test, proposed by Michelin. Tires were inflated with a mixture of 50% nitrogen and 50% oxygen and run on a 1.707 m roadwheel for up to 500 hours.

2. The Passenger Endurance Test proposed by Continental, in which the tires were run on the roadwheel for up to 240 hours.

3. An oven aging method based on tire research by Ford. The tire is inflated using the 50% nitrogen and 50% oxygen mixture, heated in an oven for a period of time to accelerate the aging process by speeding up chemical reactions, and thus material property changes. The tire may be studied for material property changes or run on a roadwheel to determine any change in durability.

The material and chemical properties of the tire structural components were measured for new tires and for tires after each of the candidate aging methods. Over 90% of tire failures recorded by NHTSA in its recall and complaint database involve the tire tread and belt area. The wire-coat skim compound that is the rubber compound directly adhered to the steel belts, and the wire-coat wedge compound between the steel belt plies are directly involved in these failures. Therefore, the tire shoulder area of the tires was studied in the most detail. The properties of the components tended to change in the same direction versus increased time of service in Phoenix or increased time of laboratory aging on each candidate method. That is, the hardness, modulus, cross-link density, and oxygen content tended to increase, while the tensile strength, ultimate elongation, peel adhesion, and flex properties tended to decrease over time. All of these changes are consistent with the proposed mechanism of thermo-oxidative aging.

The changes in properties of indentation modulus, ultimate elongation, modulus at 100% elongation, and peel adhesion in the wire skim-coat and wedge areas of the laboratory-aged tires were compared to the same changes in tires taken from service in Phoenix. The changes in the properties tended to be progressively greater as the time on a roadwheel test or in an oven aging test increased. In general, the longest roadwheel test times showed the same level of change in properties as tires with 1 to 3 years of service in Phoenix. Oven aging at the most severe conditions tended to show the same level of change in properties as tires with 3 to over 6 years of service in Phoenix. Oven aging at 3 weeks produced very little change. Oven aging for 6 weeks at 60° to 70°C or 12 weeks at 55°C produced changes in properties similar to those found after roadwheel testing, that is approximately equivalent to 1 to 3 years of service in Phoenix. Aging for 8 weeks at 65°C produced material changes similar to those seen after 4 to greater than 6 years of service. For the three of the six tire models, the hardness decreased during roadwheel testing or service in Phoenix, but increased during oven aging. This was found to correlate to the use of a reinforcing thermoset resin in the compounds of these tires, which would be expected to have non-reversible softening during repeated flexing, and hardening with increased temperature without flexing (see modulus profiles for Type H tire in Appendix 1). The mechanical energy of a break-in cycle softened these compounds and was incorporated into the Phase 3 testing.

The slope of the plot of log(ultimate elongation) versus log(modulus at 100% extension) corresponds to the type of aging of rubber compounds.(9) A slope near -0.75 indicates that the rubber compound has experienced thermo-oxidative aging. All of the tires from Phoenix service showed slopes near -0.75 in the wire skim-coat and wedge compounds. The slopes for most tires exposed to roadwheel aging or oven aging were not close to -0.75. The increase in the oxygen content for the skim-coat, wedge or innermost tread compounds of tires during roadwheel aging was also significantly less than for tires during service in Phoenix. The oxygen content of the fill gas in tires after 6 weeks of oven aging had decreased from an initial average of approximately 45% O_2 to approximately 35% O_2. As a result, the current phase of testing will include venting the fill gas and re-inflating with the 50% O_2 gas at weekly intervals.

Selected oven aged tires were tested in Phase 2 using a stepped-up-load test to compare the structural integrity after aging to that of a new tire. Most tires failed at loads much higher than their rated load capacity, and are not necessarily expected to show correlation to failures that may happen in normal tire service. Tires aged for 3 weeks showed no failures below 100% of their rated load. Parallel to the results from the physical property changes, tires aged 3 weeks at 70°C tended to have longer running times to failure than tires aged for 3 weeks at 60°C. Two tire models (See Table 11 for Phoenix retrieved tire information) showed no decrease in roadwheel time even after aging at the most severe conditions of 8 weeks at 65°C, even though tire model L showed the greatest loss in physical properties of the skim-coat and wedge compounds during aging. Two other tire models showed failures below 100% load only at aging times of 8 weeks at 65°C. These models also had predicted failure times below 100% load after 5 or more years of service in Phoenix. Roadwheel testing for tire models E and H appears to be most sensitive to oven aging times, and for service in Phoenix. For tire type E, aging for 8 weeks at 65°C or service in Phoenix for 3 to 4 years produced failures below 100% of the maximum rated load for the tires. For tire type H, 6 to 8 weeks of aging at temperatures between 60°C and 70°C, or service in Phoenix for 2 to 3 years, produced failures below 100% of the maximum rated load for the tires.

The 24-hour roadwheel break-in prior to oven aging decreased the subsequent running time to failure in the test after aging was completed. If the 24 hours were added to the total running, the total running time is longer than the tires without break-in. Since the break- in was done at 100% of maximum load, direct comparisons are only possible for tires that failed at less than 34 hours on the test after aging, specifically tire models D, E and H aged 8 weeks at 65°C. Based on these comparisons, the severity of the break-in cycle was reduced from 24 hours at 120 km/h (75 mph) in Phase 2 to 23 hours at 80 km/h (50 mph) in Phase 3.

Phase 3 of the research, reported here, applies the prototype oven aging procedure to models of tires not previously tested to determine if the physical property changes and changes in whole-tire endurance found in the 6 models tested in Phase 2 are applicable to a broad range of tires.

2.0 METHODOLOGY

2.1 Test Tires

The tires tested in Phase 3 included 20 passenger and light truck tires suitable for light vehicle applications (Table 1). Tire models were selected to cover a broad range of types and brands.

Table 1. Phase 3 Tire Models

Tire Type	Application	Market	Brand	Model	Size	Load Index (Load Range)	Speed Index
B4	LT Metric	Replacement	Bridgestone	DUELER A/T 693	LT285/75R16	122 (D)	Q
B6	P Metric	OE	Bridgestone	DUELER H/T 689	P245/70R16	106	S
B7	P Metric	Replacement	Firestone	Wilderness AT I	P265/75R16	114	S
C3	P Metric	OE	Continental	CONTITRAC	P235/70R16	104	T
C5	P Metric	OE	Continental	TouringContact AS	P205/65R15	92	T
D2	P Metric	Replacement	Arizonian [Discount Tire]	Silver Edition	P195/65R15	89	S
D3	P Metric	Replacement	Dominator [Discount Tire]	All Season	P205/65R15	92	S
D4	LT Metric	Replacement	Dominator [Discount Tire]	Durango Radial A/T	LT285/75R16	122 (D)	N
D5	LT Metric	Replacement	Dominator [Discount Tire]	Sport A/T	LT265/75R16	123 (E)	Q
G2	LT Metric	Replacement	Goodyear	WRANGLER SilentArmor	LT235/85R16	120 (E)	R
O1	LT Metric	Replacement	Big O [Big O Tire]	BIGFOOT A/T (LT235)	LT235/85R16	120 (E)	Q
O2	LT Metric	Replacement	Big O [Big O Tire]	BIGFOOT A/T	LT265/75R16	123 (E)	Q
O3	P Metric	Replacement	Big O [Big O Tire]	ASPEN	P205/65R15	92	S
O5	P Metric	Replacement	Big O [Big O Tire]	MERIT FOUR SEASON	P195/65R15	89	S
P1	P Metric	Replacement	Futura [Pep Boys]	Dakota H/T	P265/75R16	114	S
P2	LT Metric	Replacement	Futura [Pep Boys]	Scrambler A/P (LT)	LT235/85R16	120 (E)	N
P3	P Metric	Replacement	Futura [Pep Boys]	Scrambler A/P (P-XL)	P235/75R15XL	108	S
R2	LT Metric	OE	Pirelli	Scorpion STR	LT265/75R16	123 (E)	R
T2	Passenger	Replacement	Toyo	800 Ultra	P235/60R16	099	T
U2	Passenger	OE	Dunlop	SP Sport 4000 DSST (Run Flat)	P225/60R17	098	T

2.2 Test Matrix

Phase 3 testing was composed of a materials property evaluation and roadwheel durability evaluation that were not symmetric in design. Depending on the particular oven test condition evaluated, between 8-20 tire models were used (Tables 2 and 3). Not all tires successfully completed the oven aging test sequence; therefore those tires were not available for post- oven material properties analysis.

Table 2. Material Properties Test Matrix

Number of Tire Models	First Test	Second Test
18	Material Properties – New Tires	N/A
10 | 8	Oven 60°C, 7 Weeks | 10 Weeks	Standard Material Properties
17	Oven 65°C, 8 Weeks – No Break-in	Standard Material Properties
18	Oven 65°C, 8 Weeks – 23hr Break-in @ 50 mph	Advanced Material Properties

Table 3. Roadwheel Test Matrix

Number of Tire Models	First Test	Second Test
20	Stepped-Up-Load Roadwheel – New Tires	N/A
17	Oven 60°C, 7 Weeks	Stepped-Up-Load Roadwheel
20	Oven 65°C, 5 Weeks	Stepped-Up-Load Roadwheel
18	Oven 65°C, 5 Weeks – 23hr Break-in @ 50 mph	Stepped-Up-Load Roadwheel

2.3 Oven Exposure

Tires were inflated with a mixture of 50% nitrogen and 50% oxygen (50/50 N_2/O_2) to their maximum rated pressure and exposed to a constant elevated temperature of 60º or 65ºC in a circulating air oven. Tires analyzed for material properties were aged for either 10 weeks at 60º or 8 weeks at 65ºC. Tires for roadwheel testing were aged for 7 weeks at 60ºC, 5 weeks at 65ºC, or 5 weeks at 65ºC following a 23-hour break-in cycle on a roadwheel at 80 km/h (tires were inflated with dry air while on the roadwheel). The tires were vented and refilled weekly with the 50/50 N_2/O_2 gas to maintain a consistent supply of oxygen for the aging process. After oven exposure, the durability on a roadwheel test and the material properties were compared to the same model of new tire.

Of the 158 tires in Phase 3 subjected to oven aging, 17 failed prior during oven aging. Post-oven inspections of these tires are in Appendix 2. Of those 17 tires that failed in the oven, 16 were light truck tires of six different models, which were oven aged at higher inflation pressures than the passenger car tires. A trend towards sidewall blister/blow-outs in the oven was observed in light truck tire designs that used radial bleeder cords,[ii] with the sidewall blister or blow-out region typically centered directly above the bleeder cord.

2.4 Material Properties Testing

The material properties and roadwheel performance were measured for new tires of each model as a baseline for oven aging comparisons. The material properties evaluated in Phase 3 are listed in Table 4. It should be noted that not every test was run on every tire. The complete list of tires used for material properties testing is shown in Table 5. All raw data used in the report are available in the public NHTSA Phoenix Dataset 5.0. (9)

[ii] Fabric cords added to the tire construction to help vent trapped gases during mold curing in order to prevent adhesion defects (*e.g.,* United States Patents 4,363,346; 5,221,382; etc.).

Table 4. Material Properties Evaluated

Material	Material Property Test	Tire Component
Advanced	Indentation Modulus, Test developed by Akron Rubber Development Laboratory[24]	Wire-coat Skim
		Wire-coat Wedge
		Tread/Shoulder Wedge
		Shoulder
Standard	Tensile Strength and Elongation, ASTM D412	Wire-coat Skim
		Wire-coat Wedge
Standard	180º Peel Adhesion, based on ASTM D413[4]	Skim Area of Belt
		Wedge Area of Belt
Standard	Fixed Oxygen, Test Developed by Akron Rubber Development Laboratory[5]	Wire-coat Skim
		Wire-coat Wedge Compound

The tires that were oven aged and designated for post-oven material properties analysis in Phase 3 are shown in Table 5. Seven of the tires failed during oven aging (indicated by the "*" next to their barcode) and could not be analyzed for post-oven material properties.

Table 5. Tires and Tests Used in Phase 3 Material Properties Testing

Tire Type	Pre-Oven Roadwheel Break-in # hrs and	Temperature, °C	Oven Aging, Weeks	Barcode	DOT TIN Number
B4	-	60	10	2211	EJLFDAC170
	23/5	65	8	2208*	ENLFDAC520
B6	-	N/A	N/A	2222	7X9LPDW320
	-	60	7	2225	7X9LPDW320
	23/5	65	8	2221	7X9LPDW190
B7	-	N/A	N/A	2249	VN73WM0010
	23/5	65	8	2234	VN73WM0010
C3	-	N/A	N/A	2444	A30846JB150
	23/5	65	8	2452	A30846JB150
C5	-	N/A	N/A	2487	ACUR3K4200
	23/5	65	8	2491	ACUR3K4200
D2	-	N/A	N/A	2371	PJC6XTLR240
	-	60	10	2377	PJC6XTLR250
	23/5	65	8	2374	PJC6XTLR240
D3	-	N/A	N/A	2387	U9URTT9310
	23/5	65	8	2386	U9URTT9310
D4	-	N/A	N/A	2430	3DYUB8W150
	-	60	10	2428	3DYUB8W150
	23/5	65	8	2425	3DYUB8W150
D5	-	60	10	2416	UPW8XDJ230
	-	65	8	2409*	UPW8XDJ240
	23/5	65	8	2413*	UPW8XDJ080
G2	-	60	7	2125*	PJ0RY5HV330
	23/5	65	8	2122*	PJ0RY5HV330
O1	-	60	10	2338	PJ0RH6LV330

Tire Type	Pre-Oven Roadwheel Break-in (hrs / km/h)	Temperature, °C	Oven Aging Weeks	Barcode	DOT TIN Number
	23/50	65	8	2334*	PJ0RH6LV3305
O2	-	60	10	2351	PJW8JLLV4305
	23/50	65	8	2348	PJW8JLLV4305
O3	-	N/A	N/A	2324	UPURTX33205
	23/50	65	8	2321	UPURTX33305
O5	-	N/A	N/A	2312	U9C6HTE3305
	-	60	10	2311	U9C6HTE3305
	23/50	65	8	2308	U9C6HTE3305
P1	-	N/A	N/A	2013	UT73B9J2705
P2	-	N/A	N/A	2028	UP0RPAL2005
	23/50	65	8	2035	UP0RPAL2005
P3	-	N/A	N/A	2018	UTHLPAN3205
	23/50	65	8	2022	UTHLPAN3205
R2	-	N/A	N/A	2136	XLW8E4232004
	-	60	10	2139	XLW8E4231604
	23/50	65	8	2134*	XLW8E4231603

*Failed during oven aging and could not be tested for material properties.

2.5 <u>Roadwheel Testing</u>

The oven aged tires that were selected for post-oven roadwheel endurance testing in Phase 3 are shown in Appendix 3. Ten of these failed during oven aging (indicated by the "*" next to their barcode) and could not be tested on the roadwheel. Tires that successfully completed the oven exposure were then tested using the stepped-up-load until catastrophic failure protocol (SUL) test for comparison with the service aged tires tested in Phase 1. Each tire was inflated, stabilized at the ambient laboratory temperature, then run continuously on a 1.707 m (67 inch) roadwheel at 120 km/h (75 mph) for four hours at 85 percent maximum load, followed by six hours at 90 percent maximum load, and then twenty-four hours at 100 percent maximum load. If the tire completed the initial roadwheel test intact (i.e., no catastrophic structural failures or significant loss of inflation pressure), the tire is stopped for a one-hour cool-down period and inspected. If the tire passed inspection, the SUL test resumes and runs the tire through additional load steps that increase by 10 percent of the maximum rated load every four hours until catastrophic structural failure. Failure times and types were compared to new tires and tires retrieved from service in Phoenix. These results have previously been reported in detail.[10]

3.0 RESULTS

3.1 Physical Property Changes

In Phase 2, the physical property changes in the laboratory could be directly compared to the changes seen in the Phase 1 tires that had been in service in Phoenix, AZ. In order to compare the changes in properties in the components of Phase 3 tires to those in Phase 1 and 2, data were normalized by setting the value of the property of a new tire equal to 100 for each model of tire. In this way, the trends were compared for consistency and magnitude of change, to ascertain if the laboratory oven aging was consistent with the type of aging seen in service and by the laboratory-aged tires in Phase 2. For instance, the peel adhesion strength for all tires of the 6 models previously tested declined with time in service as well as in laboratory aging. If these models declined similarly in peel adhesion, it supports the hypothesis that the aging types are similar. Additionally, the 6 models tested previously showed different rates and amounts of peel adhesion loss with aging. We may compare the rates of aging for these models to the 6 models previously tested. Extensive studies by Ford Motor Company compared the rate of tire aging in a circulating air oven to that of tires in service.[12] Ford calculated that the acceleration factor for oven aging at 65°C for tires inflated with a mixture of 50% N_2 / 50% O_2 was 36. That is, each week of oven aging correlates to 36 weeks of field service. Based on this work, the physical properties were studied after 8 weeks at 65°C - approximately equivalent to 5.5 years of field service - and 10 weeks at 60°C of oven aging while inflated with 50/50 N_2/O_2.

3.1.1 Indentation Modulus

The indentation modulus of rubber components of selected tires is shown in Appendix 1. The results for the shoulder region of the tire, indexed to the new tire of the same model equal to 100, are shown in Table 6. Of the six tire models collected from on-vehicle service in Phoenix, the index of each model ranged from 84 (softening) to 145 (hardening), with most tires showing little average change. Of the 16 tire models that successfully completed 23-hour roadwheel break-in @ 50 mph (80 km/h), followed by 65°C oven aging for 8 weeks, the index ranged from 79 to 154, similar to the tires from Phoenix service; note that these were different tire models from the service aged tires.

Tires of model G2 were aged both without and with the 23-hour break-in at 100 km/h on the roadwheel prior to oven exposure. Figure 1 shows the indentation modulus cross-section of the original and oven aged tires. The effect the 23 hour roadwheel break-in on the Model G2 tires prior to oven aging was to make the modulus of the shoulder slightly less than that of the new tire. Without it, the modulus increased by nearly 75%.

The presence of diffusion-limited oxidation in the tread compounds would disqualify oven aging as an accelerated aging method, since no such effect was detected in service aged tires tested in (6). Profiles of the indentation modulus and levels of fixed oxygen in the tread were used to test for diffusion limited oxidation (DLO) in two tire models, selected because one had a low predicted DLO and the other had a high predicted DLO, based on a computer simulation of oxidation of the tread compound in oven aging. It was noted in (6) that the simulation model tended to “over-predict” DLO at elevated temperatures probably because of “the inability of the 1-D computer model to account for the multi-dimensional wicking of oxygen, especially at elevated temperatures, throughout the carcass, steel belt layers, and, if present, the nylon plies of a tire.”

The profiles of the indentation modulus for each tire model, as new and after aging, are shown in Figure 2, charts **a** to **o**. A comparison of the profiles to the oxidation from diffusion limited oxidation (DLO) has been reported separately.[4] Changes in the indentation modulus of the tread from the service aged tires from Phoenix, tire model D with a predicted DLO of 4 $x10^{-12}$ (low predicted DLO) was compared to tire model H, with predicted DLO of 8 $x10^{-12}$ (high predicted DLO). The changes in modulus for the tires in service were consistent with oxidative aging (no DLO).

If there are changes in the oxygen available for the tread compound, there should be differences in the modulus of the center of the tread lug compared to the innermost and outermost tread region. There was no evidence of a modulus gradient for either tire D or H when retrieved from Phoenix service. Similarly, there is no evidence of a modulus gradient for tires D or H after oven aging for 8 weeks at 65°C using 50/50 N_2/O_2. Tire types D4 and O2 had predicted DLO levels of $10x10^{-12}$ and $14x10^{-12}$, respectively. The modulus profiles for these tires after oven aging at 65°C are shown in Figure 2, **h** and **j**. Tire type D4 has no indication of a gradient in tread hardness. The tread modulus of tire type O2 shows an increase in hardness near the outer edge of the tread block but no evidence of DLO in the center of the tread element after aging for 8 weeks at 65°C. Thus, based on the work done in (6) the changes in modulus for the Phase 3 oven aged tires are still compatible with the oxidative aging model, with no evidence of DLO.

Table 6. Change of Indentation Modulus in Shoulder Area of Tire

Aging Condition	Tire Type	Aging Time, Years	Relative Indentation Modulus
Phoenix Service	**B**	1.37	110.6
		2.51	110.8
		6.04	145.3
	C	1.81	91.6
		5.45	98.0
	E	0.53	96.9
		3.27	116.2
	H	1.36	83.8
		1.99	90.9
		2.99	103.0
		5.96	91.2
	L	1.24	103.6
		2.65	92.6
Aging Condition	**Tire Type**	**Aging Time, Weeks**	**Relative Indentation Modulus**
23-hour Roadwheel Break-in @ 50 mph (80 km/h) & Circulating Air Oven @ 65°C	B4	8	99.2
	B6	8	130.2
	B7	8	141.5
	C3	8	123.0
	C5	8	107.0
	D2	8	104.4
	D3	8	106.5
	D4	8	124.6
	D5	8	105.6
	O2	8	79.2
	O3	8	131.9
	O5	8	153.9
	P2	8	135.8
	P3	8	117.0
	R2	8	108.2
	G2	8	84.4
	G2[iii]	8	173.0

[iii] Tire with no break-in. Same model with break-in showed a small reduction in modulus, see Figure 1

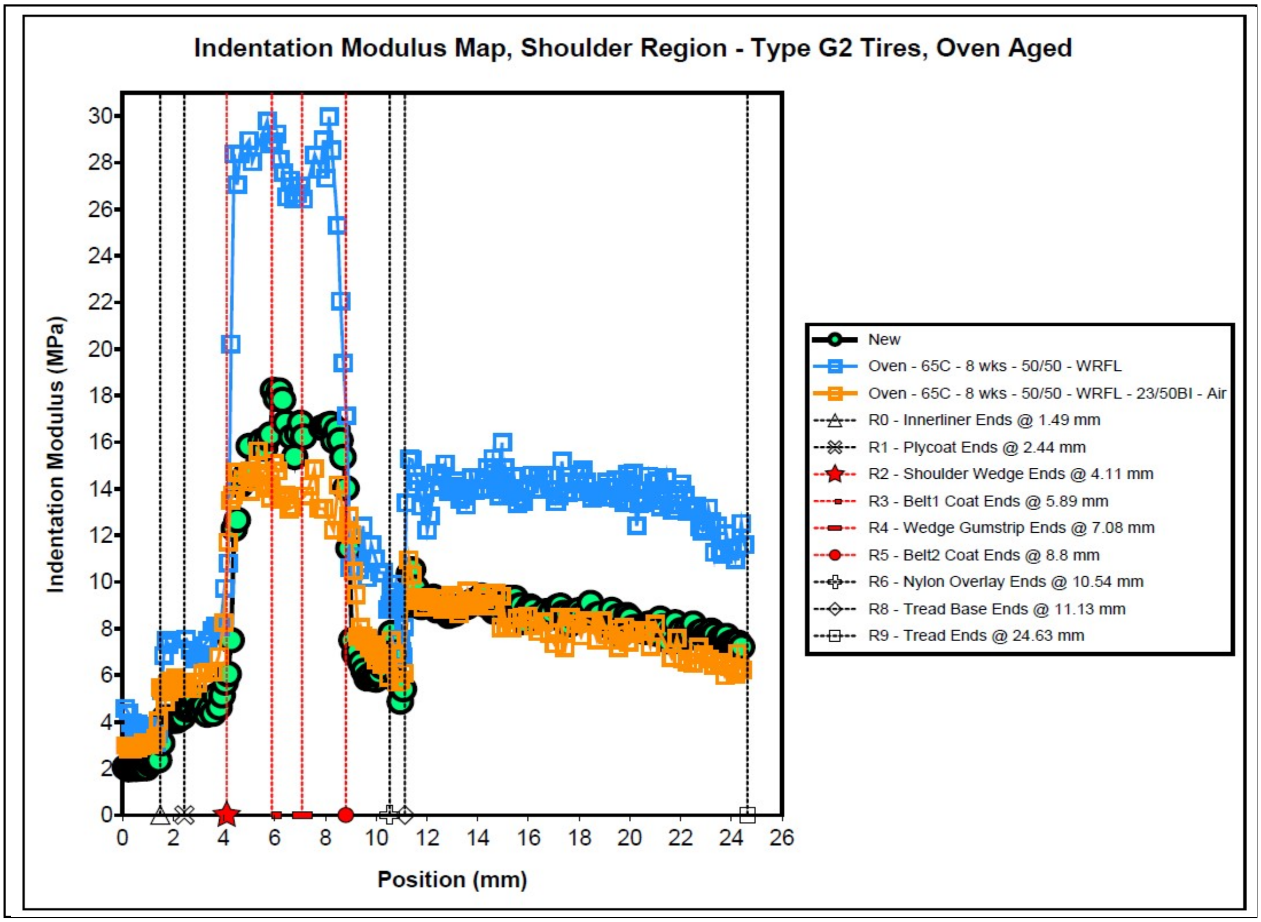


Figure 1. Indentation Modulus for Tire Model G2: Original and Oven aged for 8 Weeks at 65°C, with and without a 23-Hour Pre-Oven Roadwheel Break-in (23/50BI-Air)

Figure 2a

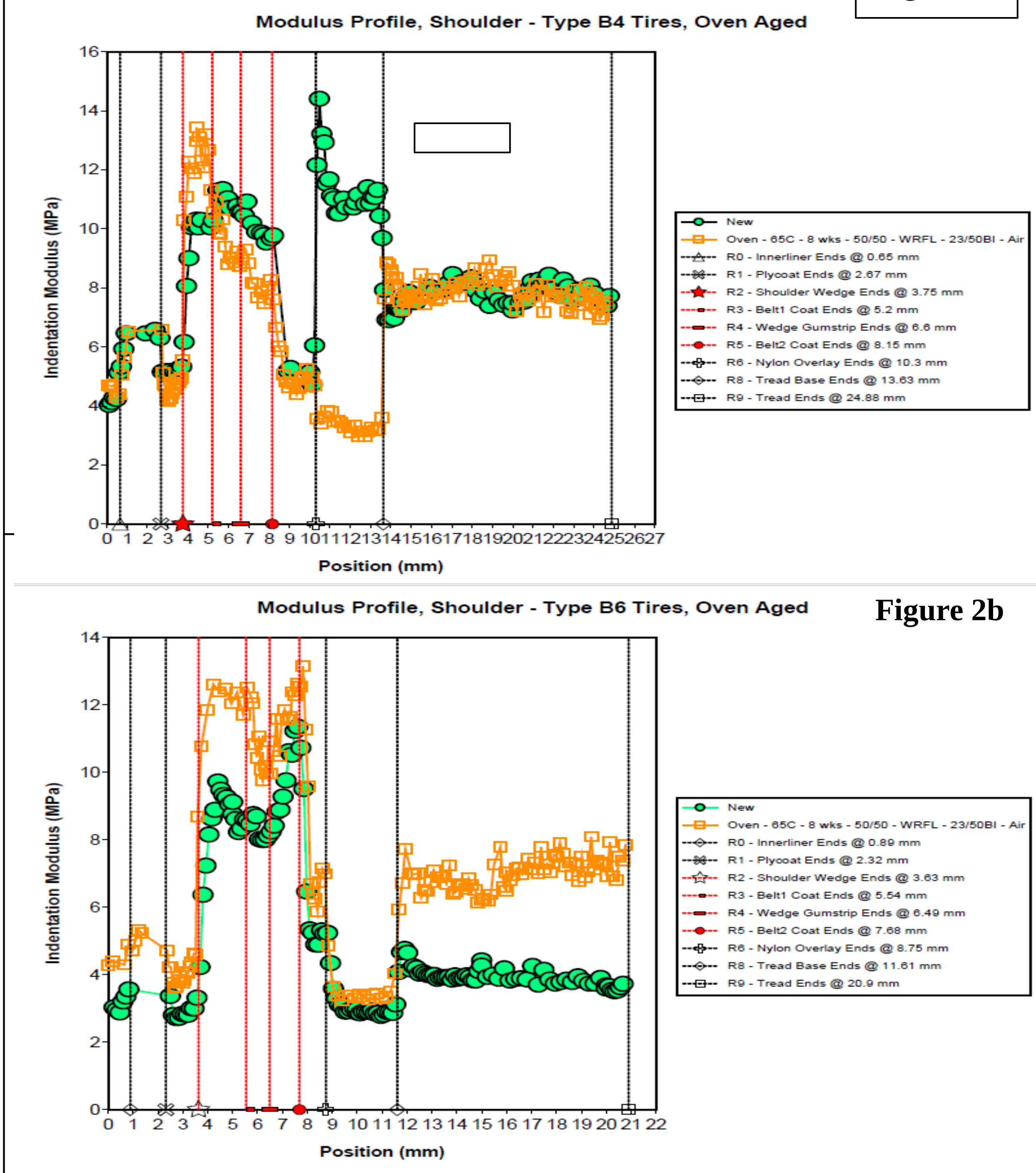
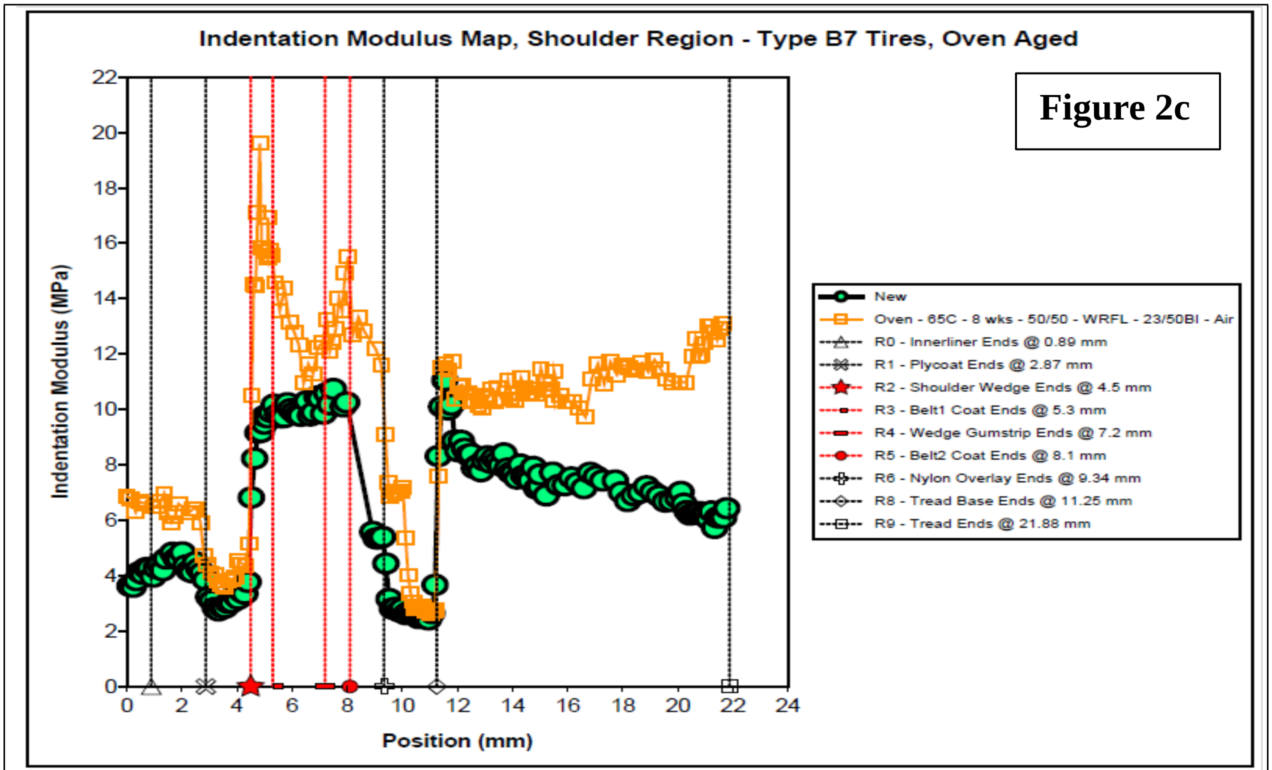
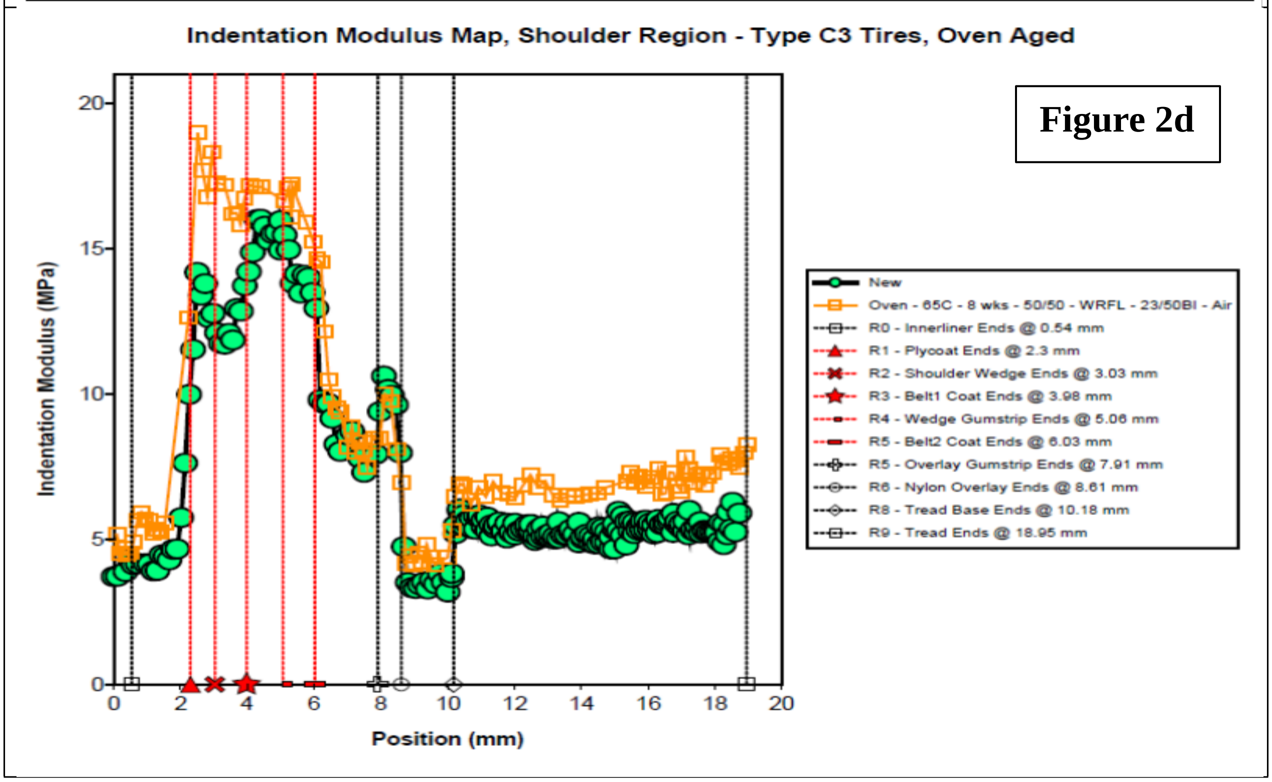
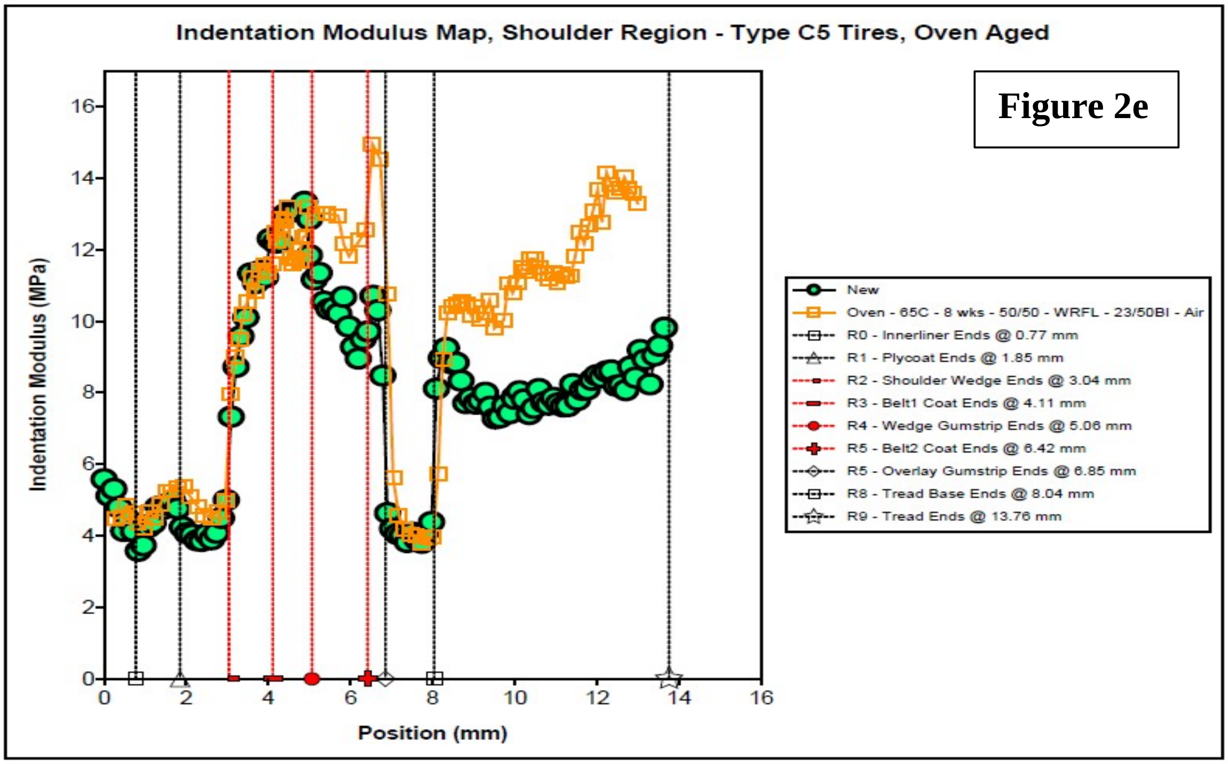


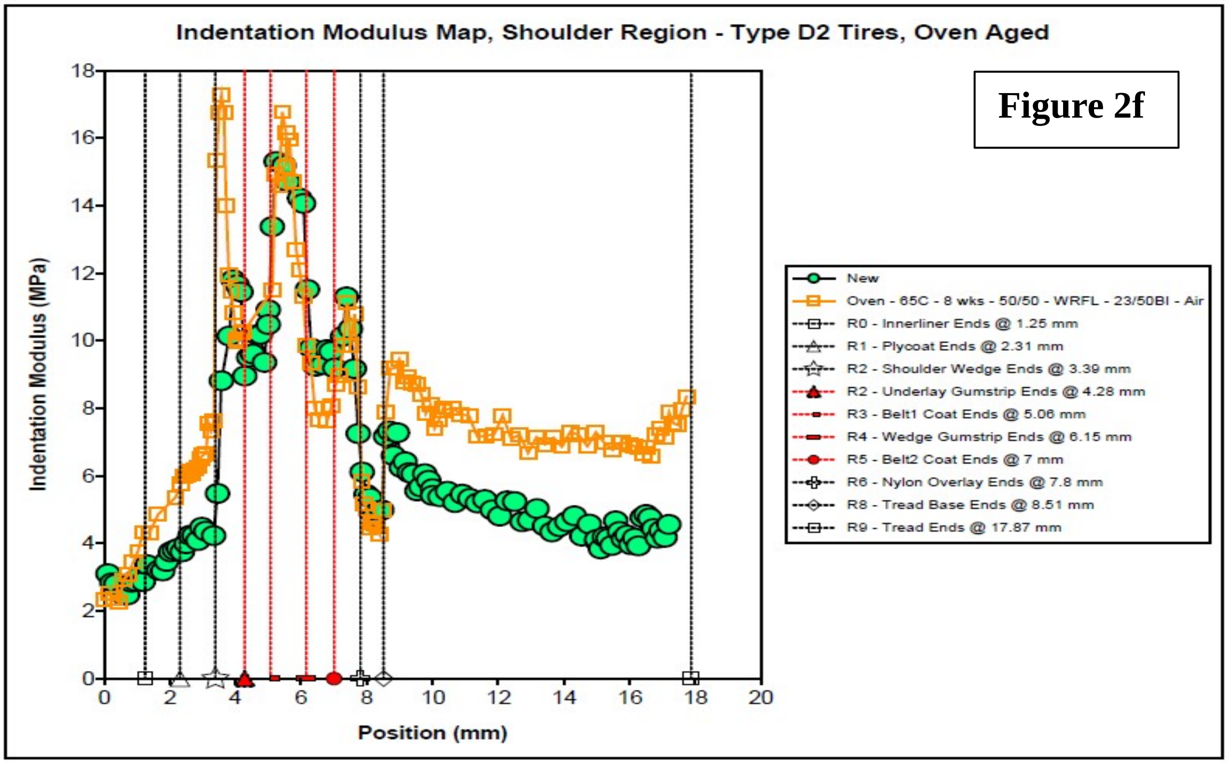
Figure 2b


Indentation Modulus Map, Shoulder Region - Type B7 Tires, Oven Aged
Figure 2c
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 0.89 mm
R1 - Plycoat Ends @ 2.87 mm
R2 - Shoulder Wedge Ends @ 4.5 mm
R3 - Belt1 Coat Ends @ 5.3 mm
R4 - Wedge Gumstrip Ends @ 7.2 mm
R5 - Belt2 Coat Ends @ 8.1 mm
R6 - Nylon Overlay Ends @ 9.34 mm
R8 - Tread Base Ends @ 11.25 mm
R9 - Tread Ends @ 21.88 mm

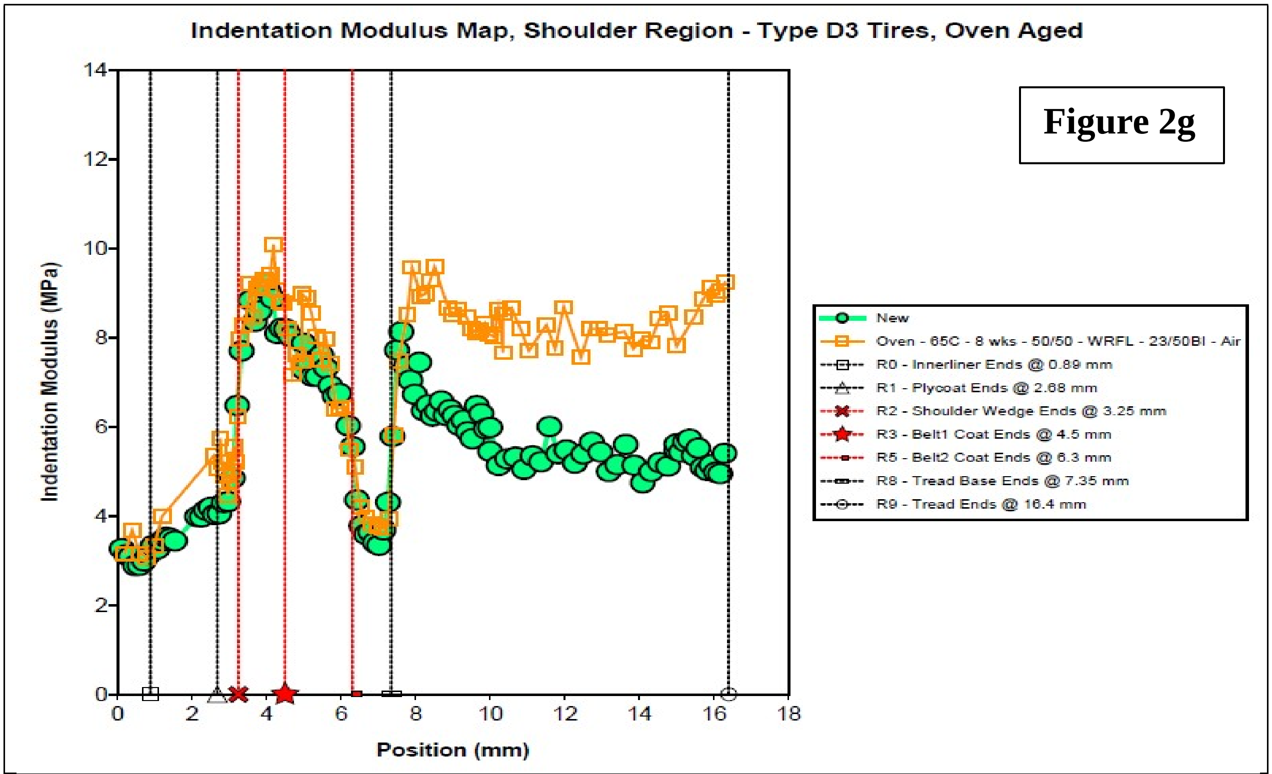

Indentation Modulus Map, Shoulder Region - Type C3 Tires, Oven Aged
Figure 2d
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 0.54 mm
R1 - Plycoat Ends @ 2.3 mm
R2 - Shoulder Wedge Ends @ 3.03 mm
R3 - Belt1 Coat Ends @ 3.98 mm
R4 - Wedge Gumstrip Ends @ 5.06 mm
R5 - Belt2 Coat Ends @ 6.03 mm
R5 - Overlay Gumstrip Ends @ 7.91 mm
R6 - Nylon Overlay Ends @ 8.61 mm
R8 - Tread Base Ends @ 10.18 mm
R9 - Tread Ends @ 18.95 mm

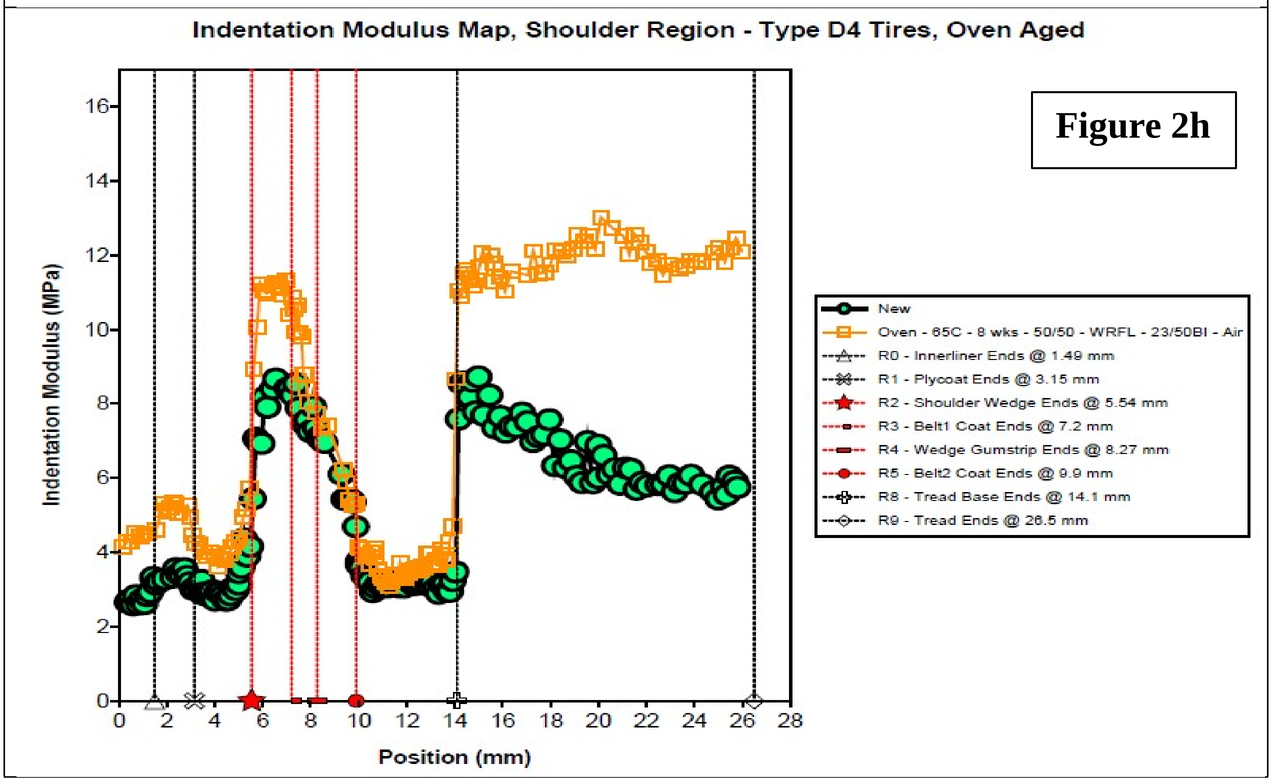


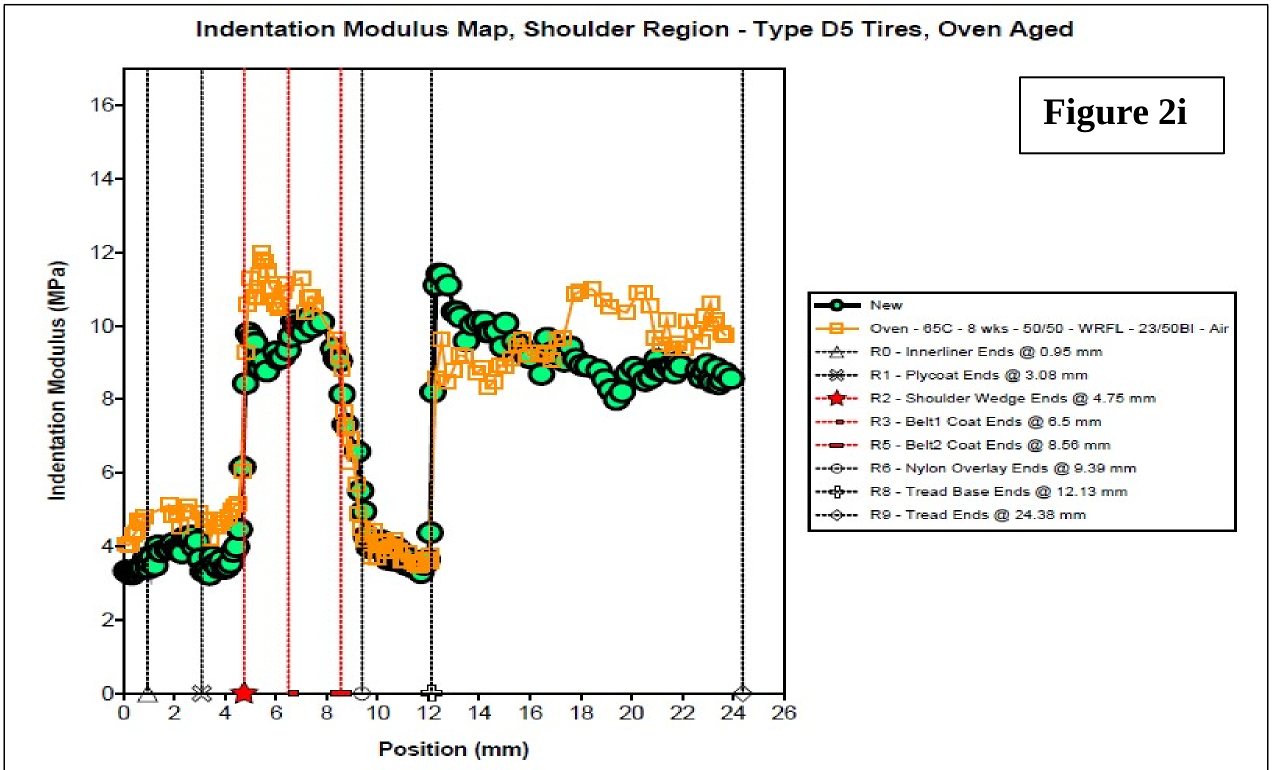
Indentation Modulus Map, Shoulder Region - Type C5 Tires, Oven Aged
Figure 2e
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 0.77 mm
R1 - Plycoat Ends @ 1.85 mm
R2 - Shoulder Wedge Ends @ 3.04 mm
R3 - Belt1 Coat Ends @ 4.11 mm
R4 - Wedge Gumstrip Ends @ 5.06 mm
R5 - Belt2 Coat Ends @ 6.42 mm
R5 - Overlay Gumstrip Ends @ 6.85 mm
R8 - Tread Base Ends @ 8.04 mm
R9 - Tread Ends @ 13.76 mm

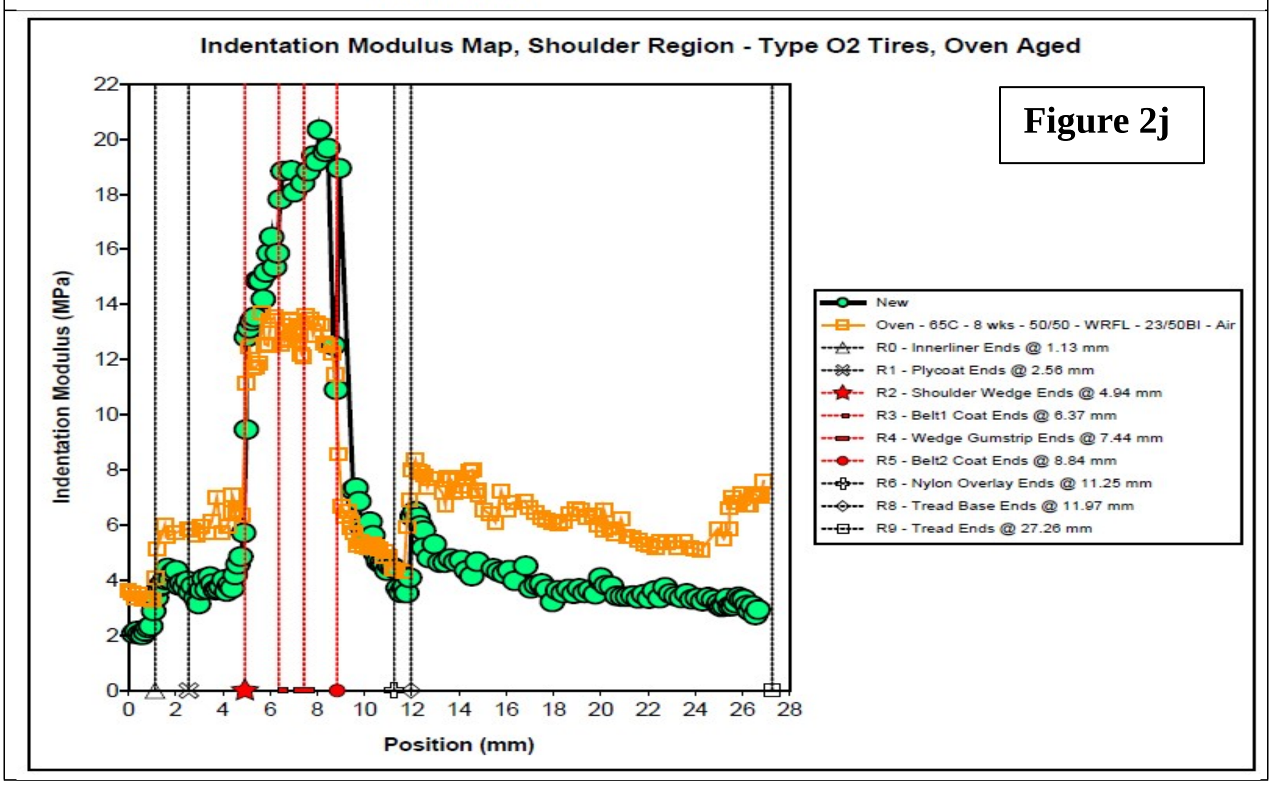


Indentation Modulus Map, Shoulder Region - Type D2 Tires, Oven Aged
Figure 2f
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 1.25 mm
R1 - Plycoat Ends @ 2.31 mm
R2 - Shoulder Wedge Ends @ 3.39 mm
R2 - Underlay Gumstrip Ends @ 4.28 mm
R3 - Belt1 Coat Ends @ 5.06 mm
R4 - Wedge Gumstrip Ends @ 6.15 mm
R5 - Belt2 Coat Ends @ 7 mm
R6 - Nylon Overlay Ends @ 7.8 mm
R8 - Tread Base Ends @ 8.51 mm
R9 - Tread Ends @ 17.87 mm


Indentation Modulus Map, Shoulder Region - Type D3 Tires, Oven Aged
Figure 2g
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 0.89 mm
R1 - Plycoat Ends @ 2.68 mm
R2 - Shoulder Wedge Ends @ 3.25 mm
R3 - Belt1 Coat Ends @ 4.5 mm
R5 - Belt2 Coat Ends @ 6.3 mm
R8 - Tread Base Ends @ 7.35 mm
R9 - Tread Ends @ 16.4 mm


Indentation Modulus Map, Shoulder Region - Type D4 Tires, Oven Aged
Figure 2h
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 1.49 mm
R1 - Plycoat Ends @ 3.15 mm
R2 - Shoulder Wedge Ends @ 5.54 mm
R3 - Belt1 Coat Ends @ 7.2 mm
R4 - Wedge Gumstrip Ends @ 8.27 mm
R5 - Belt2 Coat Ends @ 9.9 mm
R8 - Tread Base Ends @ 14.1 mm
R9 - Tread Ends @ 26.5 mm


Indentation Modulus Map, Shoulder Region - Type D5 Tires, Oven Aged
Figure 2i
Indentation Modulus (MPa)
Position (mm)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 0.95 mm
R1 - Plycoat Ends @ 3.08 mm
R2 - Shoulder Wedge Ends @ 4.75 mm
R3 - Belt1 Coat Ends @ 6.5 mm
R5 - Belt2 Coat Ends @ 8.56 mm
R6 - Nylon Overlay Ends @ 9.39 mm
R8 - Tread Base Ends @ 12.13 mm
R9 - Tread Ends @ 24.38 mm


Indentation Modulus Map, Shoulder Region - Type O2 Tires, Oven Aged
Figure 2j
Indentation Modulus (MPa)
Position (mm)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 1.13 mm
R1 - Plycoat Ends @ 2.56 mm
R2 - Shoulder Wedge Ends @ 4.94 mm
R3 - Belt1 Coat Ends @ 6.37 mm
R4 - Wedge Gumstrip Ends @ 7.44 mm
R5 - Belt2 Coat Ends @ 8.84 mm
R6 - Nylon Overlay Ends @ 11.25 mm
R8 - Tread Base Ends @ 11.97 mm
R9 - Tread Ends @ 27.26 mm

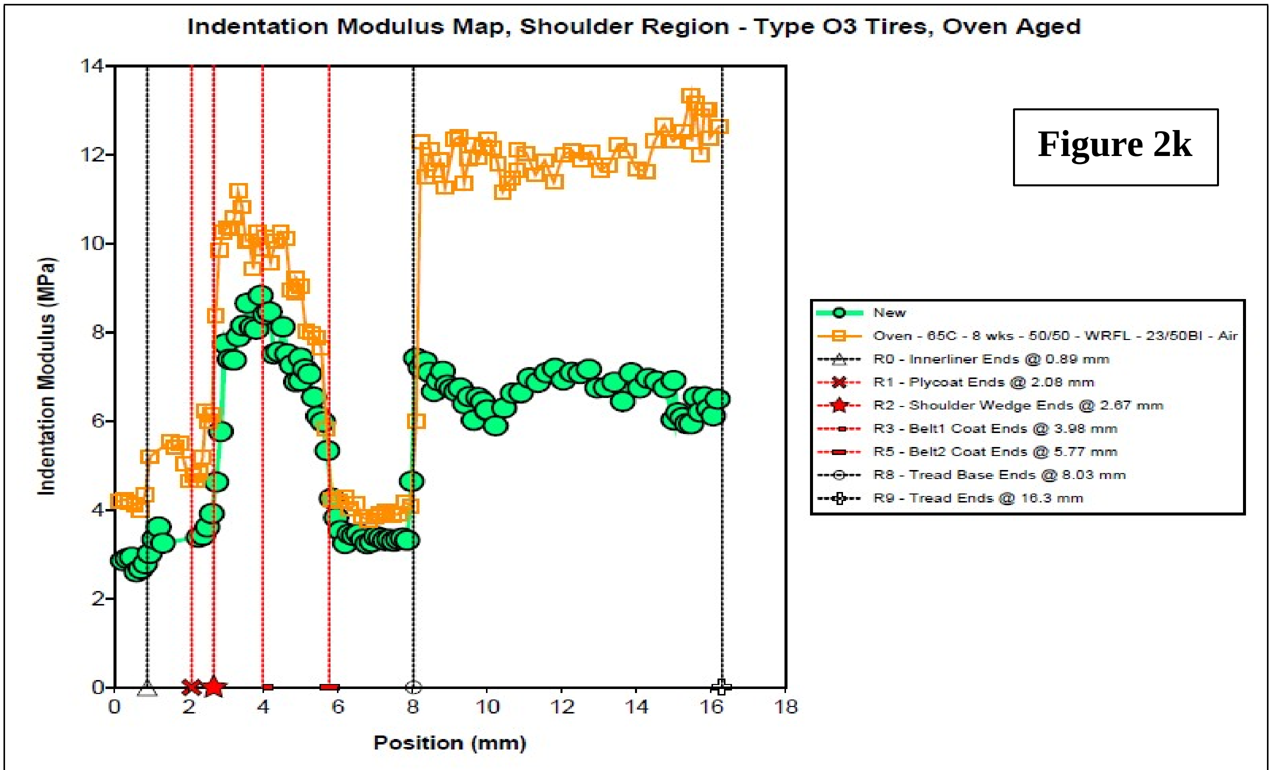


Figure 2k

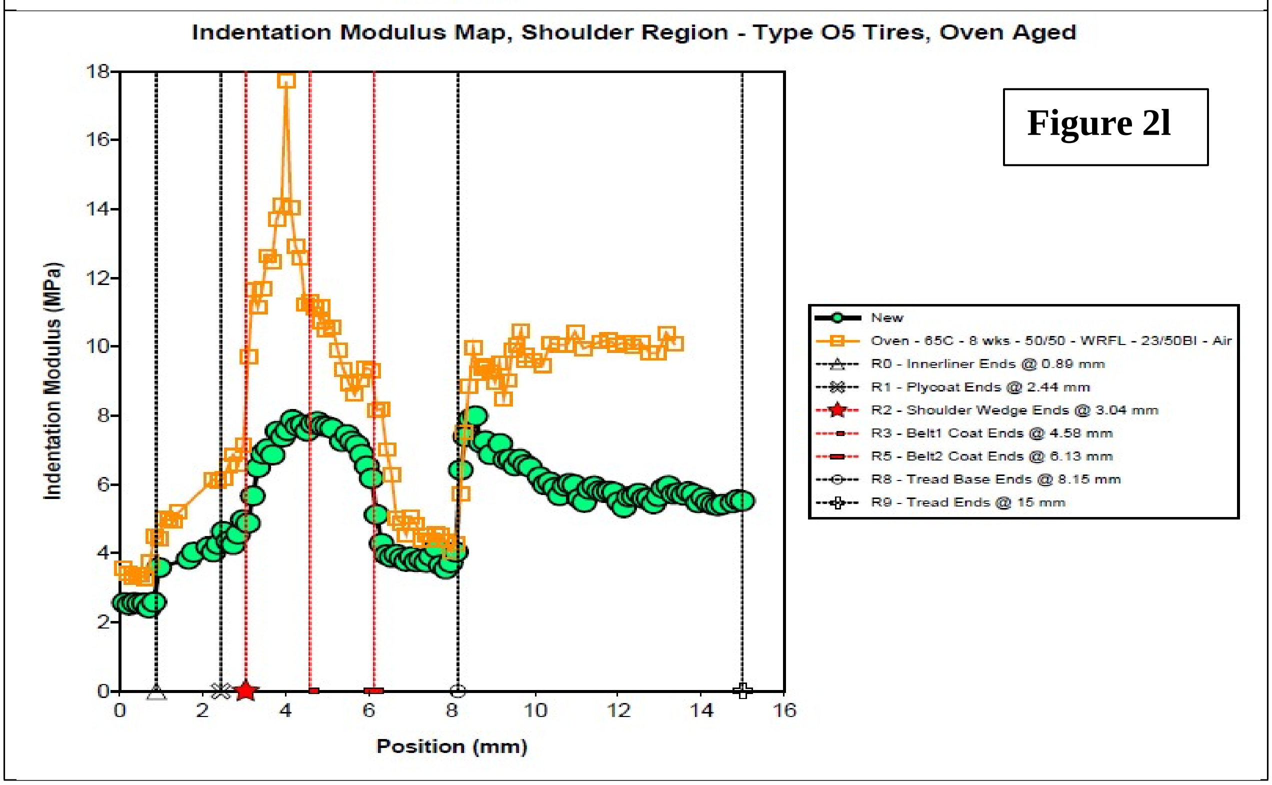
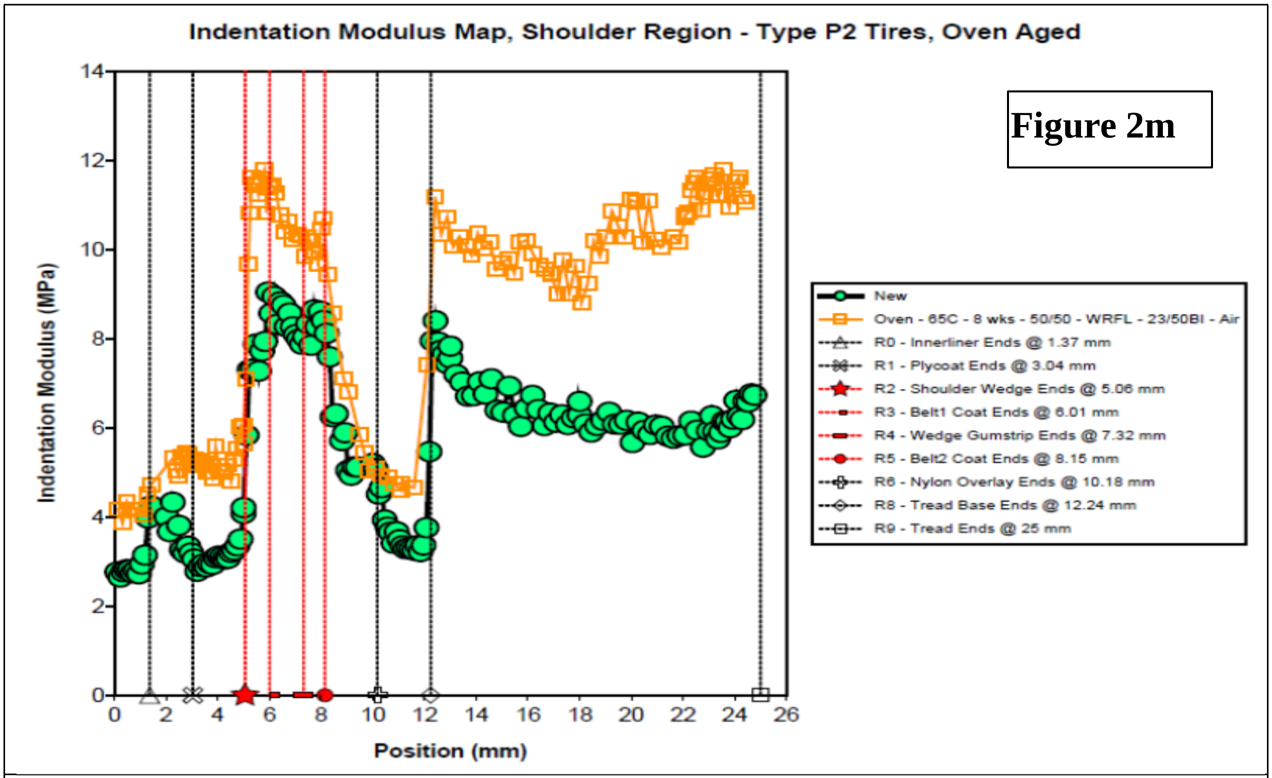
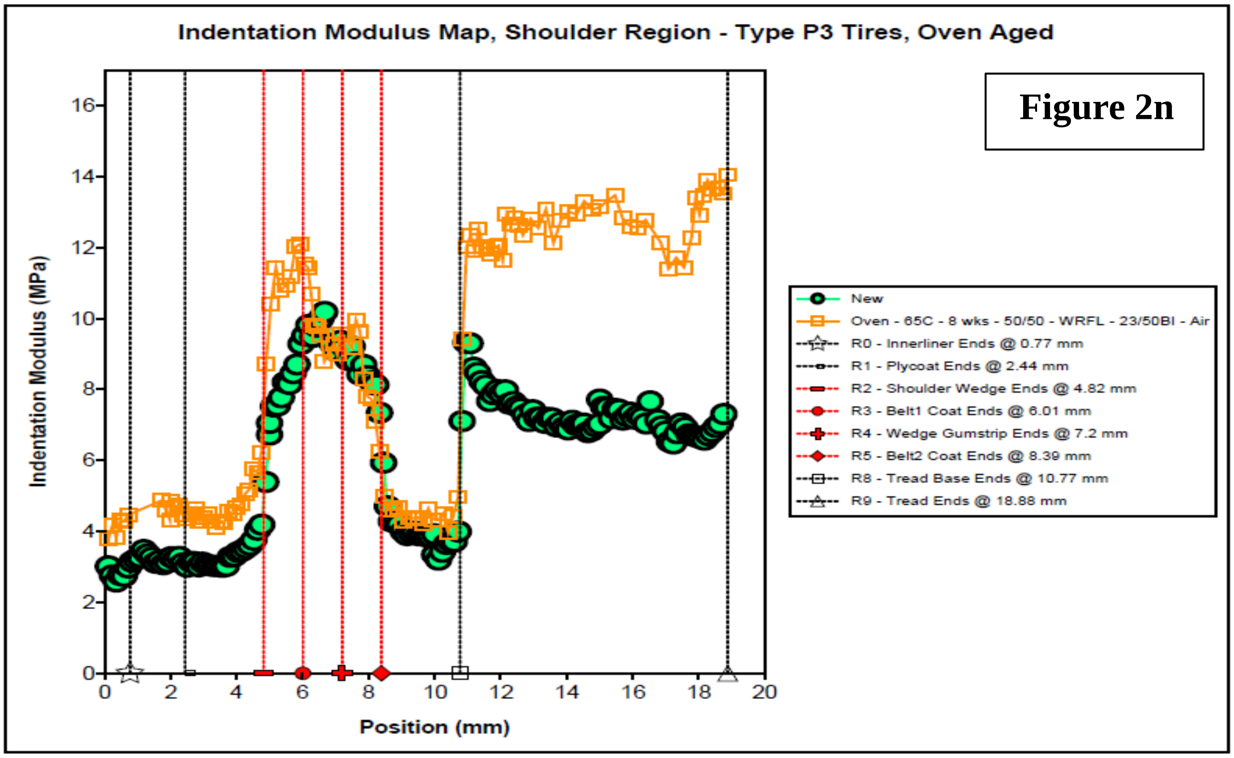


Figure 2l



Indentation Modulus Map, Shoulder Region - Type P2 Tires, Oven Aged
Figure 2m
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 1.37 mm
R1 - Plycoat Ends @ 3.04 mm
R2 - Shoulder Wedge Ends @ 5.06 mm
R3 - Belt1 Coat Ends @ 6.01 mm
R4 - Wedge Gumstrip Ends @ 7.32 mm
R5 - Belt2 Coat Ends @ 8.15 mm
R6 - Nylon Overlay Ends @ 10.18 mm
R8 - Tread Base Ends @ 12.24 mm
R9 - Tread Ends @ 25 mm



Indentation Modulus Map, Shoulder Region - Type P3 Tires, Oven Aged
Figure 2n
Indentation Modulus (MPa)
Position (mm)
New
Oven - 65C - 8 wks - 50/50 - WRFL - 23/50BI - Air
R0 - Innerliner Ends @ 0.77 mm
R1 - Plycoat Ends @ 2.44 mm
R2 - Shoulder Wedge Ends @ 4.82 mm
R3 - Belt1 Coat Ends @ 6.01 mm
R4 - Wedge Gumstrip Ends @ 7.2 mm
R5 - Belt2 Coat Ends @ 8.39 mm
R8 - Tread Base Ends @ 10.77 mm
R9 - Tread Ends @ 18.88 mm

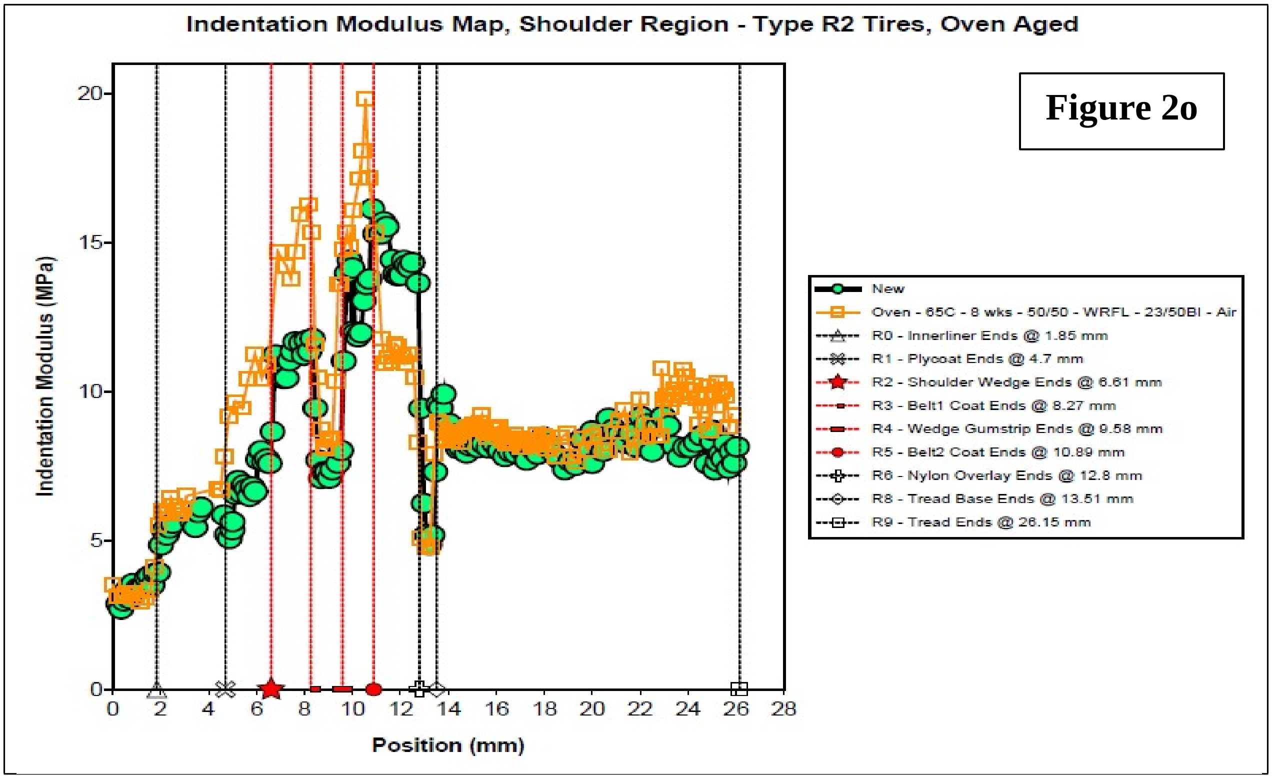


Figure 2. Indentation Modulus Profiles of New Tires and Tires Aged 8 Weeks at 65° C

3.1.2 Tensile Strength and Elongation of Skim-Coat Compound

Tensile strength and elongation of the rubber compound were measured according to the method in ASTM D 412. The modulus of the skim-coat compound for tires in the Phase 1 study increased during service in Phoenix, with an average modulus value of 145% after 2.9 years of service. Samples at the longest service time (five to seven years) reached up to 200% of the modulus found in a new tire. The average modulus values of the skim-coat compounds are shown in Table 7. After either 10 weeks at 60°C or 8 weeks at 65°C, the modulus values of the Phase 3 tires increased to an average of 180% of the corresponding new tires, with some models increasing to nearly 300% of the original modulus values. The tensile strength values for the Phoenix tires retained an average of 70% of their original elongation and 90% of their original tensile strength values, while the oven aged tires retained 40% of their elongation and 60% of their tensile strength values after either 10 weeks at 60°C or 8 weeks at 65°C.

The rate of a chemical reaction is described by the Arrhenius equation[iv] shown below.**[14]** From this equation, the rate constant for an average service-year in Phoenix can be calculated. Assuming the tire is driven 4% of the time**[12]** and the average temperature during operation is 60°C,**[13]** and that the remaining time is a resting temperature of 25°C, the exponential term of the rate constant is 1.59^{-15}. For aging 8 weeks at 65°C, the exponential term of the rate constant is 1.03^{-14} or the equivalent of 6.5 years of average service in Phoenix. For aging 10 weeks at 60°C, the term is 7.69^{-15} or the equivalent of 4.8 years of average service in Phoenix. The relative increase for the modulus, reduction in tensile strength to break, and reduction in ultimate elongation for the oven aged tires compared to the tires in Phoenix are consistent with this calculation. Tire types D2, D4, and O5 were aged at both conditions and the average results for each aging condition are compared in Table 8. Consistent with the calculated state of aging predicted from the Arrhenius equation, aging 8 weeks at 65°C resulted in higher modulus and lower tensile strength to break and ultimate elongation values than did aging 10 weeks at 60°C.

Equation 1. Arrhenius Equation for Oxidation of Natural Rubber

$$\mathbf{k = Ae^{-(Ea/RT)}}$$

Where: k = Rate Constant for Reaction
A = Prefactor
Ea = Energy of Activation (for Natural Rubber ~96,400 joules / mole)[14]
R = Ideal Gas Constant (8.3145 joules / Kelvin / mole)
T = Temperature, Kelvin

[iv] The rate of oxidation is also proportional to the concentration of reactants. In addition, there are numerous processes taking place in the rubber compounds, such as reaction with antioxidants and diffusion of O_2. However, since most processes can be described by an exponential function similar to that proposed by Arrhenius, the relative rates of aging were compared using this term.

Table 7. Relative Values of Modulus, Elongation and Tensile Strength for Skim-Coat Compound

Tire Type	Years in Service		Modulus @ 50%	Modulus @ 100%	Modulus @ 200%	Elongation at Break	Ultimate Tensile Strength
B	0.44		91.9	106.7	110.1	100.1	107.8
	0.93		123.3	131.8	132.9	89.2	107.1
	1.36		133.9	143.0	139.9	85.7	105.8
	2.26		103.9	120.9	125.7	77.7	89.5
	2.51		166.3	174.9	162.4	64.3	88.9
	2.53		114.0	136.1	143.0	70.9	90.6
	4.66		179.5	198.6	185.1	60.4	95.0
	5.54		147.2	172.5	169.0	63.8	91.3
	6.04		153.2	177.7	171.5	58.0	85.4
	6.1		136.8	149.6	146.6	73.6	93.2
	1.92		151.4	162.9	153.1	77.1	98.6
	2.05		159.8	160.4	160.9	69.1	101.4
C	4.55		199.5	207.6	193.6	53.5	77.9
D	4.56		150.2	172.7	173.3	76.2	104.6
	6.8		212.8	212.9	187.2	54.2	76.8
	1.58		123.0	124.7	118.4	82.0	94.1
E	1.43		156.9	155.7	148.5	73.8	93.9
	2.83		189.4	181.1	160.9	62.3	85.1
	3.02		178.9	174.8	158.0	67.2	90.4
	1.36		95.8	109.6	117.5	79.2	93.9
	1.5		123.3	132.1	134.4	72.8	94.1
	1.55		81.6	114.3	112.2	67.8	82.7
H	1.99		93.8	110.1	117.2	68.4	79.0
	2.99		138.8	150.9	153.2	54.3	79.2
	4.7		166.2	182.9		25.4	45.6
	1.51		131.2	128.3	119.8	70.2	81.9
L	1.53		127.8	124.5	115.3	80.9	92.0
	1.93		101.1	97.7	94.8	96.3	89.9
	4.47		146.6	152.9		55.9	76.7
Tire Type	**Temperature**	**Weeks in Oven**	**Modulus @ 50%**	**Modulus @ 100%**	**Modulus @ 200%**	**Elongation at Break**	**Ultimate Tensile Strength**
B6	60	7	147.1	161.9	166.9	58.8	77.6
	65	8	177.4	187.9	196.1	37.4	55.4
B7	65	8	187.9	181.7	168.2	37.5	56.5
C3	65	8	305.3	282.7		26.6	62.1
C5	65	8	182.6	131.0		31.6	46.3
D2	60	10	114.9	114.8	114.0	68.2	65.6
	65	8	114.6	102.3	93.9	63.1	47.9
D3	65	8	171.3	161.9		43.0	54.4
D4	60	10	162.2	164.3	154.5	50.1	67.3
	65	8	238.3	218.6		31.6	49.9
O3	65	8	171.1	156.4	141.6	52.0	66.1
O5	60	10	199.1	190.5	169.2	46.2	69.5
	65	8	290.7	246.0		33.9	62.8

Tire Type	Temperature	Weeks in Oven	Modulus @ 50%	Modulus @ 100%	Modulus @ 200%	Elongation at Break	Ultimate Tensile Strength
P2	65	8	210.3	238.4		26.3	49.2
P3	65	8	196.0	179.6	176.8	36.0	52.5
R2	60	10	184.0	192.1	153.9	39.9	67.9

Table 8. Relative Measurement of Properties of Skim-Coat Compound after Aging

Property Measured	Aging Condition		Statistically Different at 95% Confidence
	8 weeks at 65°C, % of Original Value	10 weeks at 65°C, % of Original Value	
Modulus @ 50% Elongation	214.5	158.7	No
Modulus @ 100% Elongation	189.0	156.5	No
Tensile Strength to Break	53.5	67.5	Yes
Ultimate Elongation	42.9	54.8	No

The slope of log (Ultimate Elongation at Break, %) versus log (Modulus at 100% Strain, MPa), often referred to as Ahagon slopes, were calculated for the Phase 3 tires. A slope near -0.75 for these Ahagon plots has been shown to correlate to oxidative (Type I) aging of rubber compounds.[8] Reductions in elongation with less change in modulus are associated with anaerobic (Type II) aging, which would be indicated by a less-steep negative slope or even a positive slope. Anaerobic aging associated with chain scission (Type III) is usually associated with temperatures in excess of 90ºC. The slopes of the Ahagon plots for the skim-coat compounds are shown in Table 9. All of the tire types from Phoenix service have slopes near -0.75, indicating that during service in Phoenix the skim-coat compound of tires underwent oxidative aging. Nearly all of the Ahagon slopes of the oven aged samples are consistent with oxidative aging (i.e., near -0.75). Tire types C5 and D2 had little change in modulus with a significant reduction in elongation, evidence that there may have been anaerobic aging either during the extended break-in or in the oven. The wire-coat compounds for both of these tires were calculated to contain approximately 2-phr[v] resin reinforcement which may have influenced the results.[5] For those tires tested at both aging conditions, there was no significant difference in the slope for the two different aging temperatures.

[v] phr = parts of resin per hundred parts rubber.

Table 9. Ahagon Slopes for Skim-Coat Compound

Tire Type	Ahagon Slope, from Log(Elongation) Vs. Log(100% Modulus)		
	Phoenix Tires	**Oven aged 8 weeks @ 65°C**	**Oven aged 10 weeks @ 60°C**
B	-0.76		
C	-0.81		
D	-0.91[vi]		
E	-0.86[vii]		
H	-1.00		
L	-0.44		
B6		-0.64	
B7		-0.61	
C3		-0.78	
C5		-0.23	
D2		-0.05	-0.36
D3		-0.57	
D4		-0.68	-0.71
O3		-0.68	
O5		-0.83	-0.83
P2		-0.65	
P3		-0.57	
R2			-0.71

[vi] Based on a single tire in Phoenix service
[vii] Modulus decreases during service in Phoenix, therefore slope does not include new tire data.

3.1.3 Tensile Strength and Elongation of Wedge Compound

The wedge compound is the compound between the wire belts in the shoulder area where 90% of tire failures reported to NHTSA in the published defects reports occurred.[15] This compound may be the same composition as the skim-coat compound, or it may be a special formulation placed between the wire skim-coat compounds in the shoulder area during the building process.

The modulus of the wedge compound for tires in the Phase 1 study increased during service in Phoenix, with an average modulus value of 140% after 2.9 years of service. Samples at the longest service time (five to seven years) reached up to 180% of the modulus found in a new tire. The average modulus values of the skim-coat compounds are shown in Table 10. After either 10 weeks at 60°C or 8 weeks at 65°C, the modulus values of the Phase 3 tires increased to an average of 140% of the corresponding new tires, with some models increasing to nearly 250% of the original modulus values (Table 11). The tensile strength values for the Phoenix tires retained an average of 70% of their original elongation and 85% of their original tensile strength values, while the oven aged tires retained 40% of their elongation and 60% of their tensile strength values after either 10 weeks at 60°C or 8 weeks at 65°C. Like the skim-coat compound, this is consistent with the aging rates calculated from the Arrhenius equation. The average values for tire types D2, D4, and O5 aged at both conditions are shown in Table 12. The values are very similar to the results for the skim compound and also indicate that the aging for 8 weeks at 65°C appears to be more severe than aging for 10 weeks at 60°C.

Table 10. Relative Values for Modulus, Tensile strength, and Elongation for Wedge Compound – Phoenix-Retrieved Tires

Tire Type	Years in Service	Modulus @ 50%	Modulus @ 100%	Modulus @ 200%	Elongation at Break	Ultimate Tensile
B	0.44	93.7	104.9	109.5	97.9	107.4
	0.93	117.9	130.9	131.2	83.9	100.3
	1.36	128.6	138.6	139.5	83.7	105.6
	2.26	105.4	122.8	128.5	75.9	90.1
	2.51	156.0	168.3	162.3	65.7	92.1
	2.53	117.1	135.4	140.3	71.8	90.6
	4.66	170.2	187.2	175.3	60.7	90.1
	5.54	145.3	169.4	168.5	65.6	95.2
	6.04	163.0	186.4	182.1	55.4	85.3
	6.1	159.1	172.1	168.3	70.8	101.9
C	1.92	132.2	137.0	131.7	74.1	86.4

Tire Type	Years in Service	Modulus @ 50%	Modulus @ 100%	Modulus @ 200%	Elongation at Break	Ultimate Tensile
	2.05	166.3	166.5	158.6	52.9	78.3
	4.55	164.0	163.9	139.2	43.6	55.6
	4.56	140.4	149.2	142.6	66.1	81.8
	6.8	154.4	155.2	146.3	60.2	73.6
D	1.58	108.4	123.5	118.5	76.6	90.0
E	1.43	150.5	148.0	139.0	58.5	72.9
	2.83	143.8	143.7	134.3	64.9	78.7
	3.02	167.3	167.5	150.7	54.5	73.4
H	1.36	157.8	159.4	143.5	59.5	76.1
	1.5	93.4	106.9	115.1	84.7	98.2
	1.55	118.7	131.2	136.7	68.5	90.4
	1.99	87.0	106.9	117.1	79.0	92.3
	2.99	96.1	109.3	118.0	73.7	86.2
	4.7	130.4	146.0	150.8	58.2	85.0
L	1.51	147.7	141.1	120.7	62.6	77.2
	1.53	150.3	146.7	133.4	62.6	80.3
	1.93	131.5	128.1	119.6	74.7	87.6
	4.47	177.7	175.1	.	40.9	61.0

Table 11. Relative Values for Modulus, Tensile strength, and Elongation for Wedge Compound – Oven aged Tires

Type	Temperature	Weeks in Oven	Modulus @ 50%	Modulus @ 100%	Modulus @ 200%	Elongation at Break	Ultimate Tensile
B6	60	7	136.4	154.9	166.1	59.7	81.8
	65	8	159.5	173.0	178.2	44.4	62.1
B7	65	8	145.7	157.3	152.9	36.8	52.7
C3	65	8	278.1	259.5	.	25.3	57.5
C5	65	8	185.3	154.4	.	38.2	54.6
D2	60	10	126.9	134.6	131.6	53.8	58.3
	65	8	113.5	109.2	94.1	53.5	41.3
D3	65	8	190.4	168.4	.	42.1	55.6
D4	60	10	148.1	154.7	150.9	54.2	71.1
	65	8	248.4	235.7	.	32.1	54.3
O3	65	8	159.9	151.3	132.5	46.6	57.6
O5	60	10	187.7	179.7	162.2	52.5	75.8
	65	8	237.5	217.2	.	36.8	60.6
P2	65	8	194.3	223.5	226.1	33.6	63.9
P3	65	8	152.8	168.5	.	33.8	45.7
R2	60	10	139.7	155.2	159.9	42.0	58.9

Table 12. Relative Measurement of Properties of Wedge Compound after Aging

Property Measured	Aging Condition		Statistically Different at 95% Confidence
	8 weeks at 65°C, % of Original Value	10 weeks at 60°C, % of Original Value	
Modulus @ 50% Elongation	199.8	154.2	No
Modulus @ 100% Elongation	187.4	156.3	No
Tensile Strength to Break	40.8	53.5	No
Ultimate Elongation	52.1	68.4	No

The slopes of the Ahagon plots for the wedge compounds are shown in Table 13. All of the tire types from Phoenix service have slopes near -0.75, indicating that during service in Phoenix the wedge compound of tires tends to age oxidatively. With the exception of type D2, the wedge compounds for the oven aged tires also had slopes near -0.75, evidence that no anaerobic aging took place. For those tires tested at both aging conditions, there was no significant difference in the slope for the two aging temperatures.

Table 13. Ahagon Slopes for Wedge Compound

Tire Type	Ahagon Slope, from Log(Elongation) Vs. Log(100% Modulus)		
	Phoenix Tires	**Oven aged 8 weeks @ 65°C**	**Oven aged 10 weeks @ 60°C**
B	- 0.77		
C	- 1.39		
D	- 0.80[viii]		
E	- 1.15		
H	- 1.17		
L	- 1.56		
B6		-0.67	
B7		-0.45	
C3		-0.69	
C5		-0.45	
D2		-0.14	-0.47
D3		-0.60	
D4		-0.75	-0.71
O3		-0.54	
O5		-0.77	-0.91
P2		-0.73	
P3		-0.48	
R2			-0.50

3.1.4 <u>Peel Adhesion</u>

Based on the observed reduction in peel adhesion force for the tires recalled during the Ford/Firestone investigation, peel adhesion was considered as a test to determine the residual durability of tires after aging or time in service. The peel adhesion behavior of the six tire types recovered from service in Phoenix has been reported.[(3)] While peel adhesion decreased with time in service, peel adhesion is not a reliable predictive measure because: i) most samples did not fail at the wire/rubber interface, but failed cohesively in the rubber compound and ii) due to the physics of the peel sample, the actual force measured is a function of rubber properties such as thickness and modulus. For the tires removed from service in Phoenix after an average of 2.99 years, both the skim-coat and the wedge areas retained an average peel adhesion of 53% of the original tires (Table 14). At the maximum service time of 5 to 7 years, the retained adhesion ranged from approximately 25% to 60% of the original adhesion. The oven aged tires

[viii] Based on a single tire in service in Phoenix

retained approximately 40% of the adhesion for both the skim- coat and wedge areas, with a range of approximately 20% to 70% (Table 15).

Table 14. Relative Peel Adhesion Values for the Skim-Coat and Wedge Compounds – Phoenix-Retrieved Tires

Tire Type	Years in Service	Peel Adhesion of Skim-Coat, % of New Tire	Peel Adhesion of Wedge, % of New Tire
B	0.44	87.8	93.2
	0.93	60.9	75.4
	1.36	56.5	64.4
	2.26	56.7	57.8
	2.51	43.5	46.7
	2.53	58.6	62.4
	5.54	48.9	54.8
	6.04	43.3	53.7
	6.1	52.6	72.4
C	1.92	55.1	41.5
	2.05	72.7	61.6
	4.55	44.3	37.8
	4.56	58.9	52.2
	6.8	55.7	47.2
D	1.58	56.0	71.4
E	1.43	64.4	68.4
	2.83	42.7	38.9
	3.02	49.1	48.6
H	1.36	78.1	62.3
	1.5	46.8	53.5
	1.55	42.3	45.0
	1.99	69.0	67.3
	2.99	44.3	47.1
	4.7	24.5	16.8
L	1.51	41.0	31.9
	1.53	35.1	26.8
	1.93	68.2	67.4
	4.47	35.4	31.6

Table 15. Relative Peel Adhesion Values for the Skim-Coat and Wedge Compounds – Oven- Aged Tires

Type	Temperature	Weeks in Oven	Peel Adhesion of Skim-Coat, % of New Tire	Peel Adhesion of Wedge, % of New Tire
B6	60	7	40.3	43.1
	65	8	17.8	22.8
B7	65	8	20.3	22.2
C3	65	8	18.4	23.2
C5	65	8	26.0	41.6
D2	60	10	68.3	65.8
	65	8	60.7	56.0
D3	65	8	41.9	40.6
D4	60	10	51.2	46.8
	65	8	38.5	23.9
O3	65	8	31.2	35.0

Type	Temperature	Weeks in Oven	Peel Adhesion of Skim-Coat, % of New Tire	Peel Adhesion of Wedge, % of New Tire
O5	60	10	56.7	71.5
	65	8	29.9	39.8
P2	65	8	25.6	33.6
P3	65	8	36.6	46.5
R2	60	10	46.7	46.1

Table 16. Relative Measurement of Peel Adhesion after Aging

Property Measured	Aging Condition		Statistically Different at 95% Confidence
	8 weeks at 65°C, % of Original Value	**10 weeks at 60°C, % of Original Value**	
Peel Adhesion of Skim-Coat, % of New Tire	43.0	58.7	Yes
Peel Adhesion of Wedge, % of New Tire	39.9	61.4	Yes

3.1.5 Fixed Oxygen Level

Fixed oxygen is the amount of oxygen that is chemically combined with the rubber compound. As noted earlier, changes in physical properties may result from thermal reactions (anaerobic aging), or from reaction with oxygen (aerobic aging). The agency examined the level of fixed oxygen in the skim, wedge, and innermost tread of six tire models collected from on-vehicle use in Phoenix after varying amounts of service. These results confirmed the aerobic chemical reactions in the shoulder region of light vehicle tires during service. The level of fixed oxygen for tires tested on the roadwheel and oven aged was measured. The normalized fixed oxygen level for varying amounts of service is shown in Table 17. Table 18 shows levels for varying amounts of oven aging. As noted, the level of fixed oxygen increases in all components for tires in service. Most tire types showed a small increase in fixed oxygen level to an average of approximately 110% of the original value. Tire types C and H showed more dramatic increases, to approximately 120% and 150% respectively, after 5 to 7 years of service. The fixed oxygen content for six tire models of the Phase 3 tires were measured and were approximately 120% to 175% of the levels of the original tires of the same model. This suggests that there was sufficient oxygen available from the 50/50 nitrogen/oxygen inflation gas to provide O_2 to the internal components of the tire during the aging time of 8 weeks at 65°C. This was also supported by the modeling of diffusion-limited oxidation in a number of tire models and has been reported separately.(6) Additionally, the level of oxidation experienced in these components of the Phase 3 tires is greater than that experienced by similar tires after 5 to 7 years in Phoenix service.

Table 17. Normalized Fixed Oxygen Level over Time – Phoenix-Retrieved Tires

Tire Type	Time in Service, years	Shoulder Area	Wedge Compound	Tread Compound
B	0.44	98.3	96.6	99.3
	0.93	101.2	99.3	113.0
	1.36	104.5	100.3	112.9
	2.26	103.5	99.9	101.0
	2.51	102.7	106.8	100.7

Tire Type	Time in Service, years	Shoulder Area	Wedge Compound	Tread Compound
	2.53	110.8	109.9	106.0
	4.66	108.4	105.4	100.0
	5.54	113.6	111.5	113.7
	6.04	113.6	110.6	135.9
	6.1	109.8	110.4	128.7
C	1.92	106.1	106.3	106.5
	2.05	102.1	98.9	106.7
	4.55	109.3	123.5	114.9
	4.56	117.4	122.9	116.9
	6.8	112.3	127.9	122.7
D	1.41	104.1	99.2	102.9
	1.58	105.3	102.3	112.5
	3.87	115.2	115.5	124.5
E	1.43	108.6	109.2	100.1
	2.83	105.6	107.8	95.0
	2.91	109.2	104.8	108.7
	3.02	104.0	105.6	94.5
H	1.36	117.0	101.0	107.2
	1.5	93.8	91.5	122.2
	1.55	100.8	96.4	119.9
	1.99	104.8	97.6	118.8
	2.99	100.9	97.4	122.3
	4.7	152.1	148.8	125.2
	5.96	144.6	139.4	138.0
L	1.06	105.8	107.9	114.9
	1.24	102.7	98.5	101.9
	1.51	106.9	92.1	120.5
	1.53	98.9	97.3	128.0
	1.93	109.3	104.5	114.0
	2.65	109.6	105.5	102.2
	4.47	106.7	104.3	119.4

Table 18. Normalized Fixed Oxygen Level over Time – Oven aged Tires

Tire Type	Temperature	Weeks in Oven	Shoulder Area	Wedge Compound	Tread Compound
B7	65	8	161.11	148.06	178.37
C3	65	8	178.63	161.95	151.09
C5	65	8	175.44	173.08	165.24
O3	65	8	136.45	139.49	.
P2	65	8	136.54	117.27	103.46
P3	65	8	127.04	119.49	110.30

3.2 Roadwheel Testing: Stepped-up-Load to Structural Failure after Oven Aging

Selected tires were subjected to testing on a 1.707 m roadwheel after they had been oven aged for varying periods of time. The conditions of the roadwheel test are shown in Table 19. The first 34 hours of the test are the same as those of the upgraded §571.139 Endurance test.[16]

After completing the Endurance test conditions, the tire is inspected, and passing tires are further subjected to roadwheel evaluation at loads that increase every 4 hours by increments of 10% of the maximum rated load until the tire fails. The results were compared to the average predicted data for tires removed from service in Phoenix. The results and discussion of the Phoenix service tires have been reported separately.[12] Using the Arrhenius formula in Equation 1 and conditions discussed earlier, aging seven weeks at 60°C is equivalent to 3.4 years of service and aging five weeks at 65°C is equivalent to the aging experienced by a tire with 4.0 years of service in Phoenix.

Table 19. Stepped-Up-Load Roadwheel Test Conditions

Test Stage	Duration (hours)	Load as a percentage of tire maximum load rating	
Optional Break-in	23	100% Load at 80 km/h (50 mph)	Experimental
1	4	85%	OVSC TP-139-03, Paragraph 12.6
2	6	90%	
3	24	100%	
Inspection	1		
4	4	110%	Until Failure
5	4	120%	
Etc.	4	Increment load by +10% every 4 hours until failure	

The stepped-up-load test was intended to compare the structural integrity of the tire after aging to that of a new tire. Once the test load exceeds the rated load for the tire at the test pressure, the test simulates increasingly severe amounts of overloading/underinflation (i.e., over-deflection of the tire). Where the load required to cause failure was significantly higher than 100%, relative time to failure of different tire models may not be relevant. However, it may be inferred that tires which require such higher loads to cause failure have higher structural integrity than those which fail at lower loads.

All tires tested in Phase 3 were manufactured during the 2004 to 2005 timeframe, prior to the adoption of the updated §571.139 standard. Tires tested in Phase 3 were not required to meet the more severe requirements of the §571.139 endurance test. Since the first few steps of the

Stepped-Up Load Roadwheel test follow the §571.139 [ix] endurance test, the severity of the roadwheel test used in Phase 3 exceeds the Federal endurance test performance requirements for tires of that generation.

The average and range of all passenger and light truck times to failure are shown in Figure 3. All new passenger tires, and all but one of the new light truck tires (94%), continued running to times beyond the upgraded §571.139 endurance test time of 34 hours. Tire number 2340 (Type O2) exhibited tread shoulder cracking at 29 hours Tire number 2341 (companion to Tire number 2340) failed at 43 hours by sidewall delamination and tread shoulder cracking. Tires failing during oven aging are indicated in Figure 3 as having <u>zero hours</u> on the post-oven roadwheel test. Tires failing during oven aging are listed in Appendix 2 with pictures of the post-test inspection when available.

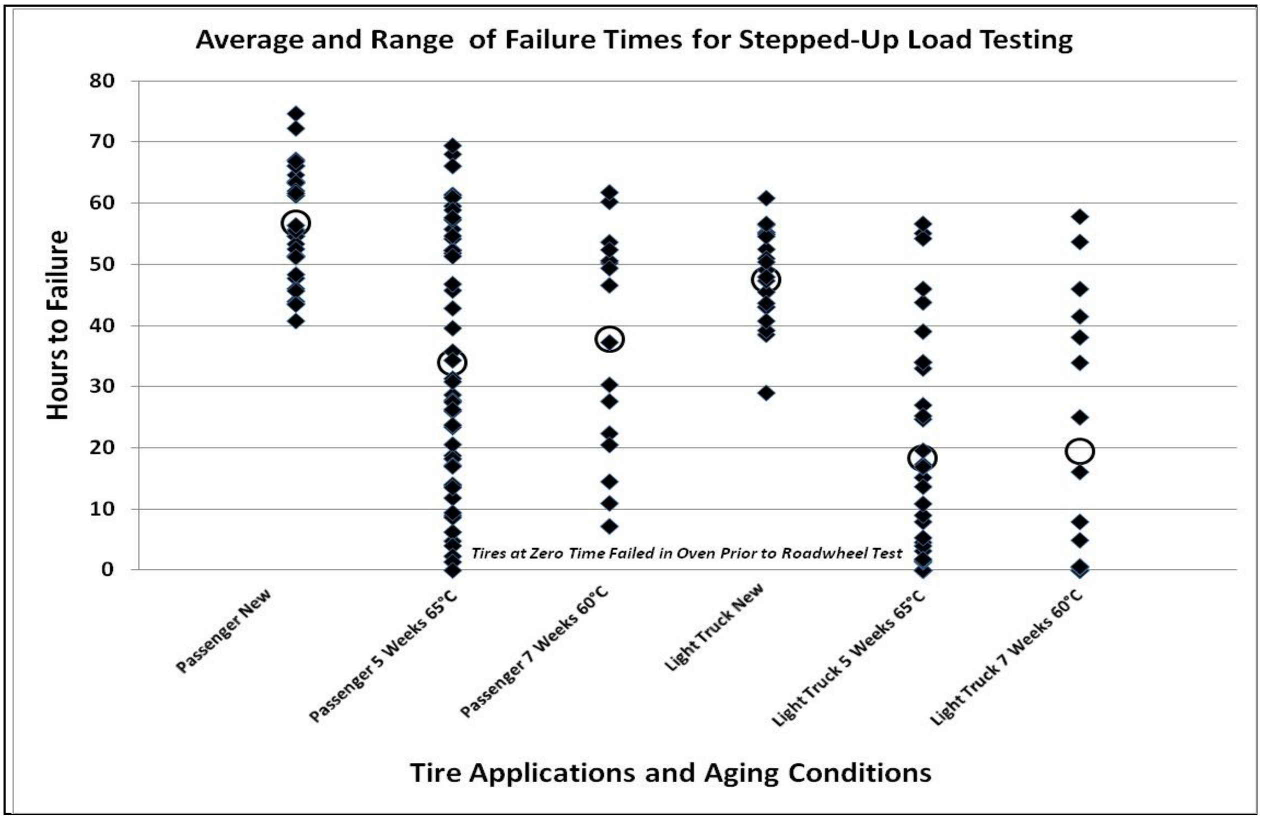


Figure 3. Average and Range of Failure Times for New Tires and Same Model of Tires after Oven Aging, Passenger and Light Truck Tires

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[ix] Previously, passenger tires were regulated by the FMVSS No. 109 (“Passenger car tires”) and light-truck tires under the separate FMVSS No. 119 (“Tires for vehicles other than passenger cars”). The FMVSS No. 119 had less severe test conditions than the FMVSS No. 109 and did not include a high-speed or bead unseat test for tires. The FMVSS No. 139 unifies regulation of the majority of passenger and light-truck tire designs for vehicles with a gross vehicle weight rating of 10,000 pounds or less. This new standard became mandatory on September 1, 2007, for non-snow tire designs and became mandatory on September 1, 2008, for designated snow tire designs. Optional compliance was permitted before those dates.

The results of the stepped-up-load test failures for passenger tires are shown in Figure 7. The green line at 34 hours represents 100% of rated load. Testing at loads above this level causes stress on parts of the tire, such as the sidewall and bead, beyond that which is expected during normal operation, often causing failures to occur in these components. The corresponding results for the individual light truck tires are shown in Figure 9.

The failure times for all tires that were aged at both 5 weeks at 65°C (without break-in) and 7 weeks at 60°C were compared. There were no significant differences at the 95% confidence level between the two aging conditions.

Tires with and without break-in were oven aged for 5 weeks at 65°C and the running times to failure compared. The average failure times, shown in Figure 4, were slightly lower for those tires that were exposed to a break-in cycle. For light truck tires, the average times were 18 hours without a break-in and 16 hours after the break-in cycle ended. For passenger tires, the averages were 33 hours without a break-in and 26 hours after the break-in cycle ended. The average failure times were compared by individual tire type, but were not statistically different between tires with and without break-in at the 95% confidence level.

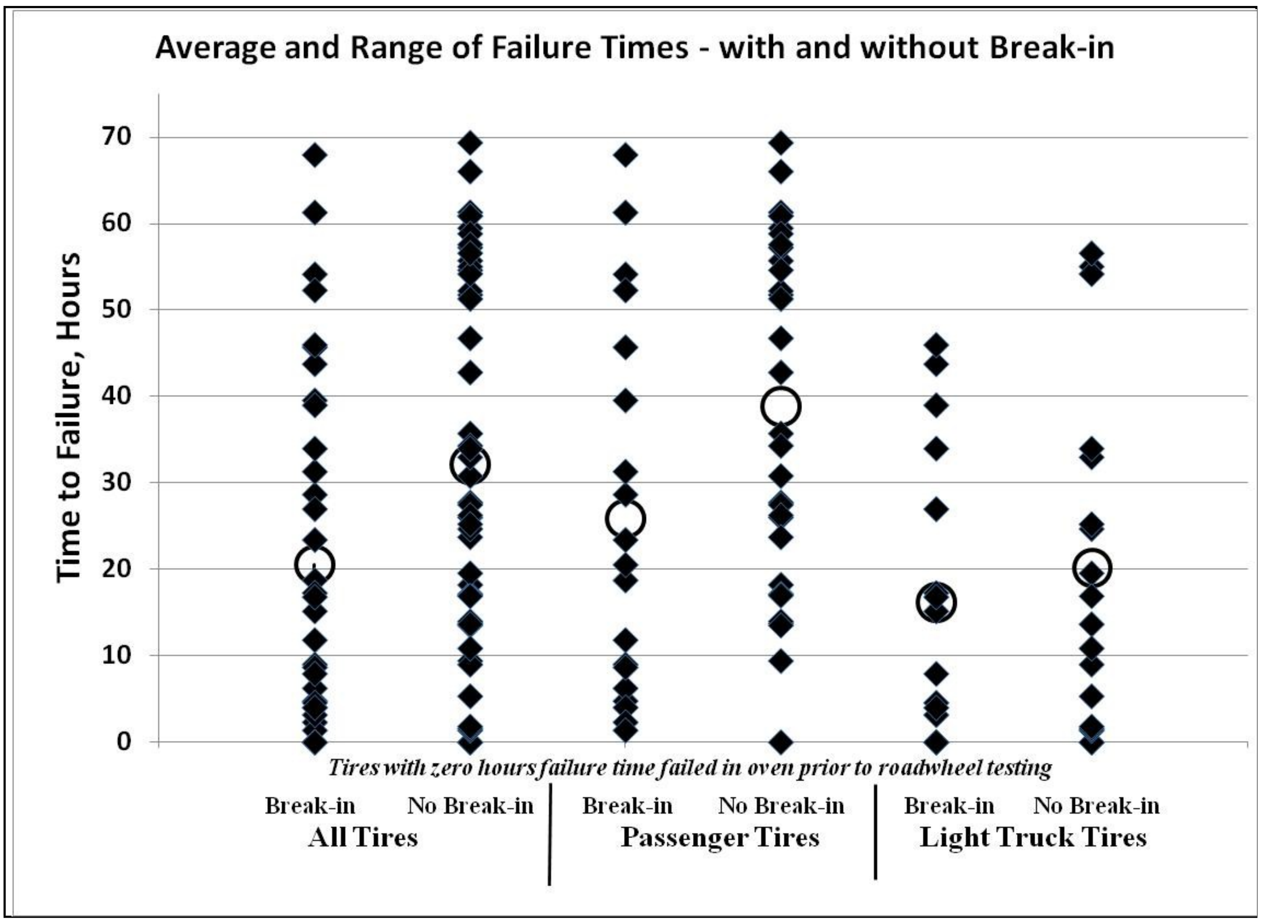


Figure 4. Failure Times for Tires Tested to Failure after Oven aging 5 Weeks at 65°C; With and Without a Roadwheel Break-in of 23 hours at 80 km/h

The passenger tire types that exhibited failures prior to 34 hours were looked at individually and the results are summarized in Table 20.

Table 20. Failure Conditions of Passenger Tire Models
(Failure Times of Less Than 34 Hours are shown in Bold)

Tire Type	Oven Temp. (°C)	Weeks Aging	Break-in	Hours to Failure	Description of Failure	Barcode
C5	New			66.07	TLC: Tread Lug Chunking	2483
				66.1	PT+B2D: Partial Tread and Belt 2 Detachment	2484
	65	5	23 hrs	1.38	BES: Belt Edge Separation	**2490**
	65	5	None	26.28	CT+B2D: Complete tread and belt 2 detachment	**2485**
				42.82	CT+B2D: Complete tread and belt 2 detachment	2486
	65	5	23 hrs	45.73	CT+B2D: Complete tread and belt 2 detachment	2489
	60	7	None	49.37	TShC+BE/BEE: Tread Shoulder Chunking with Belts Exposed/ Belt Edge Exposed	2492
				52.37	PT+B2D/BES: Partial Tread and Belt 2 Detachment/ Belt Edge Separation	2493
D2	New			45.65	TShC: Tread Shoulder Chunking	2367
				52.5	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2366
	65	5	None	26.03	BEE: Belt Edge Exposed	2368
				14	SwCr: Sidewall Cracking	2372
	65	5	23 hrs	18.75	TShCr: Tread Shoulder Cracking	2373
				20.55	BEE: Belt Edge Exposed	2369
	60	7	None	30.33	ShR/BEL: Shoulder Rupture / Belt Edge Loosened	2376
				37.75	SwR+DL: Sidewall Rupture with Delamination	2375
D3	New			43.45	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2379
				51.2	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2380
	65	5	None	0	FIO: Failed in oven at week 5 due to: Shoulder delamination	**2381**
	65	5	23 hrs	2.32	BEE: Belt Edge Exposed	**2385**
				4.03	CT+B2D: Complete Tread and Belt 2 Detachment	**2384**
O3	New			40.75	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2315
				55.63	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2314
	65	5	None	17	CT+B2D: Complete Tread and Belt 2 Detachment	2316
	65	5	23 hrs	28.67	CT+B2D: Complete Tread and Belt 2 Detachment	2319
				31.33	TC: Tread Chunking	2320
	60	7	None	14.5	B1P1D: Belt 1 to Carcass Detachment	2323

Tire Type	Oven Temp. (°C)	Weeks Aging	Break-in	Hours to Failure	Description of Failure	Barcode
O5	New			55.6	CT+B2D: Complete Tread and Belt 2 Detachment	2301
				55.62	CT+B2D: Complete Tread and Belt 2 Detachment	2302
	65	5	None	9.42	CT+B2D: Complete Tread and Belt 2 Detachment	2304
				17.17	CT+B2D: Complete Tread and Belt 2 Detachment	2303
	65	5	23 hrs	6.25	CT+B2D: Complete Tread and Belt 2 Detachment	2306
				8.67	CT+B2D: Complete Tread and Belt 2 Detachment	2307
	60	7	None	10.95	CT+B2D: Complete Tread and Belt 2 Detachment	2309
				7.2	CT+B2D: Complete Tread and Belt 2 Detachment	2310
P1	New			46	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2002
				47.72	TShC: Tread Shoulder Chunking	2001
	65	5	None	34.33	TC: Tread Chunking	2004
				35.75	TShC+BE/BES: Tread Shoulder Chunking with Belts Exposed / Belt Edge Separation	2003
	65	5	23 hrs	4.78	TShCr: Tread Shoulder Cracking	2007
				23.43	TShCr: Tread Shoulder Cracking	2006
	60	7	None	22.37	TShCr: Tread Shoulder Cracking + Belt Edge	2010
P3	New			43.57	PT+B2D: Partial Tread and Belt 2 Detachment	2015
				43.92	BEE: Belt Edge Exposed	2014
				48.33	TShC+BE/BdTuCr: Tread Shoulder Chunking with Belts Exposed/Bead Turn-up Cracking	2053
				51.42	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2054
	65	5	None	27.75	B1P1D/CaR: Belt 1 to Carcass Detachment/Carcass Rupture	2016
				30.83	TC: Tread Chunking	2017
	65	5	23 hrs	9	CT+B2D: Complete Tread and Belt 2 Detachment	2021
				11.83	B1P1D: Belt 1 to Carcass Detachment	2020
	60	7	None	20.5	CT+B2D: Complete Tread and Belt 2 Detachment	2023
	60	7	None	27.62	TShC: Tread Shoulder Chunking	2024
T2	New			67.1	BdTuR: Bead Turn-up Rupture of Body Ply Cords with Radial Cracking	2664
				66.83	BdTuCr: Bead Turn-up Cracking	2665
	65	5	None	46.78	BES: Belt Edge Separation	2668
	65	5	None	51.33	BES: Belt Edge Separation	2669

Tire Type	Oven Temp. (°C)	Weeks Aging	Break-in	Hours to Failure	Description of Failure	Barcode
U2	New			63.55	ILD/ShR: Innerliner Damage/ Shoulder Rupture	2078
				63.27	ShR: Shoulder Rupture	2079
	65	5	None	59.52	ILD: Innerliner Damage	2082
	65	5	None	61.34	ILD: Innerliner Damage	2083

At failure times of less than 34 hours, with the load equal to or less than the rated load of the tire, indicating the stresses on individual components could have been experienced in normal service conditions. The 28 out of 57 oven aged passenger tires (49%) that exhibited visible failures in less than 34 hours of roadwheel testing are summarized in Figure 5.

Approximately 2/3 of these failures occurred in the belt area, with another 22% of failures taking place in the shoulder area. As discussed previously, over 90% of failures consumers reported to NHTSA happened in the belt and shoulder area. Failures by tread cracking accounted for 6% of the visible failures in the oven aged tires, with a small number of carcass and sidewall failures.

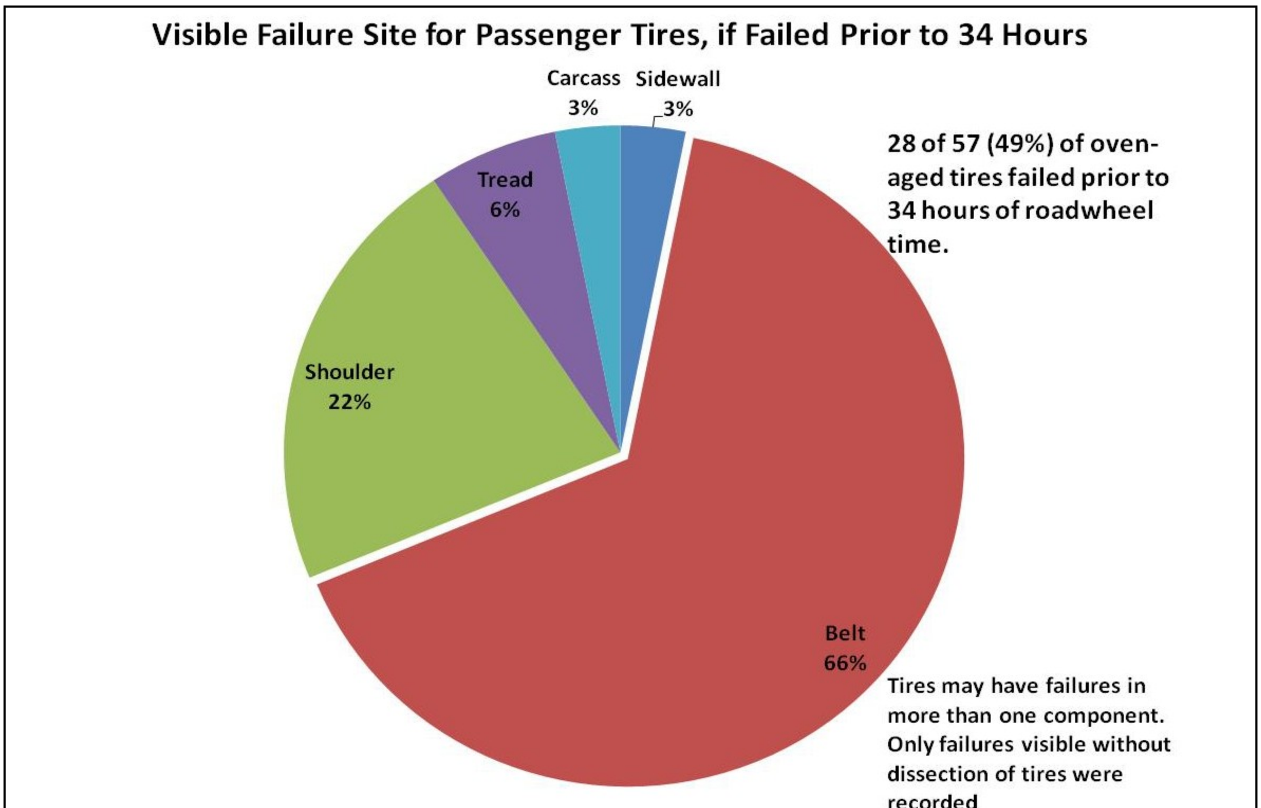


Figure 5. Site of Failure for Passenger Tires with Failure Times Less Than 34 Hours

In Phase 1 and Phase 2 of this work tires retrieved from service in Phoenix, as well as new tires of the same model, were subjected to SUL testing. The range of results from this work is displayed in Figure 6. The average failure time is shown as the solid black line. New tires on average exceeded the 34-hour failure time. The average failure time for tires retrieved from

Phoenix service continued to exceed 34 hours, indicated by the green reference line, until approximately 3.7 years of time in service. The tire model with the least and greatest change are shown by the dashed blue lines. Some tire models easily exceeded the 34-hour failure time even after 6 years of service in Phoenix, while other models did not reach an average 34 hour failure time, even when new. A viable artificial aging procedure should show a similarly broad range of discrimination among tire models after aging.

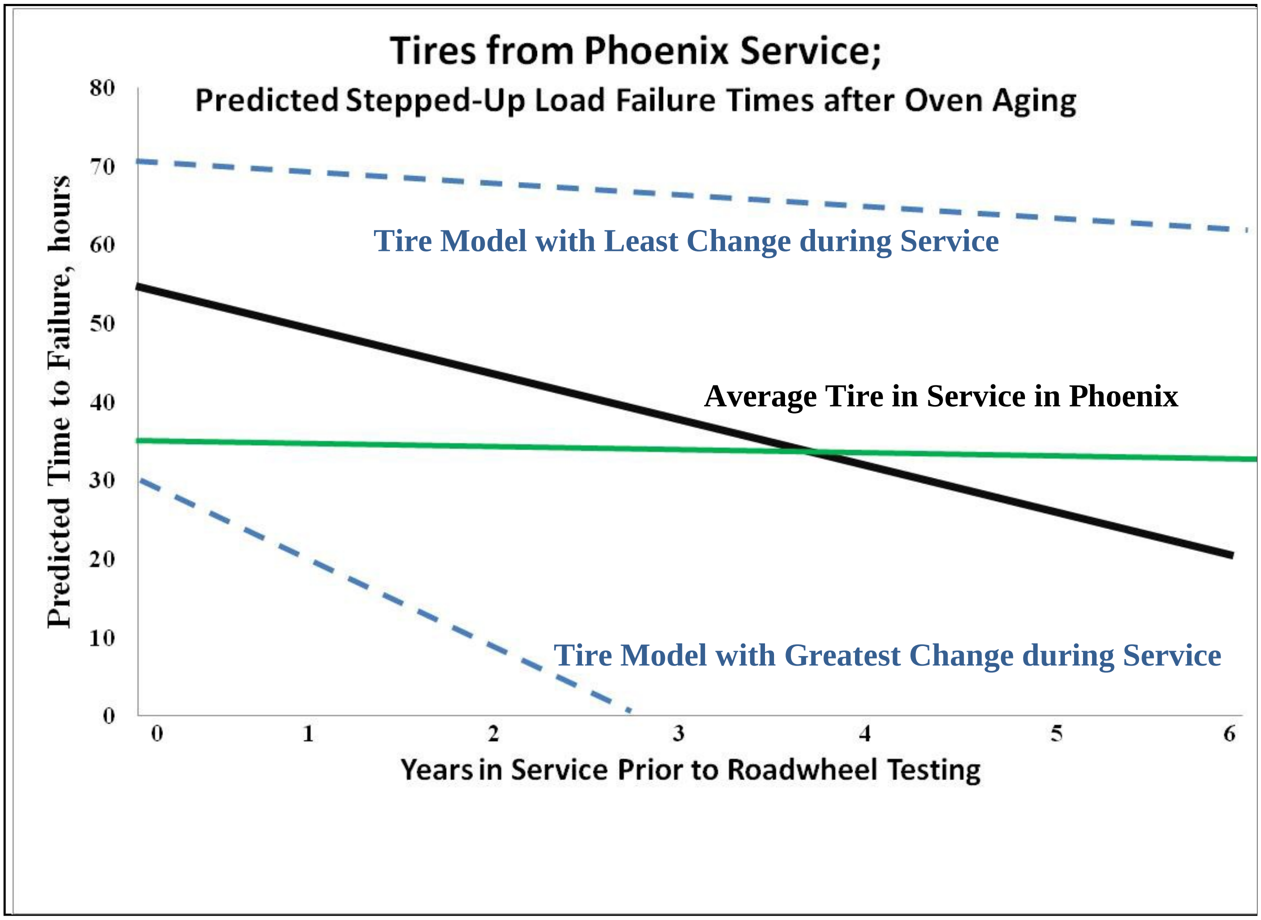
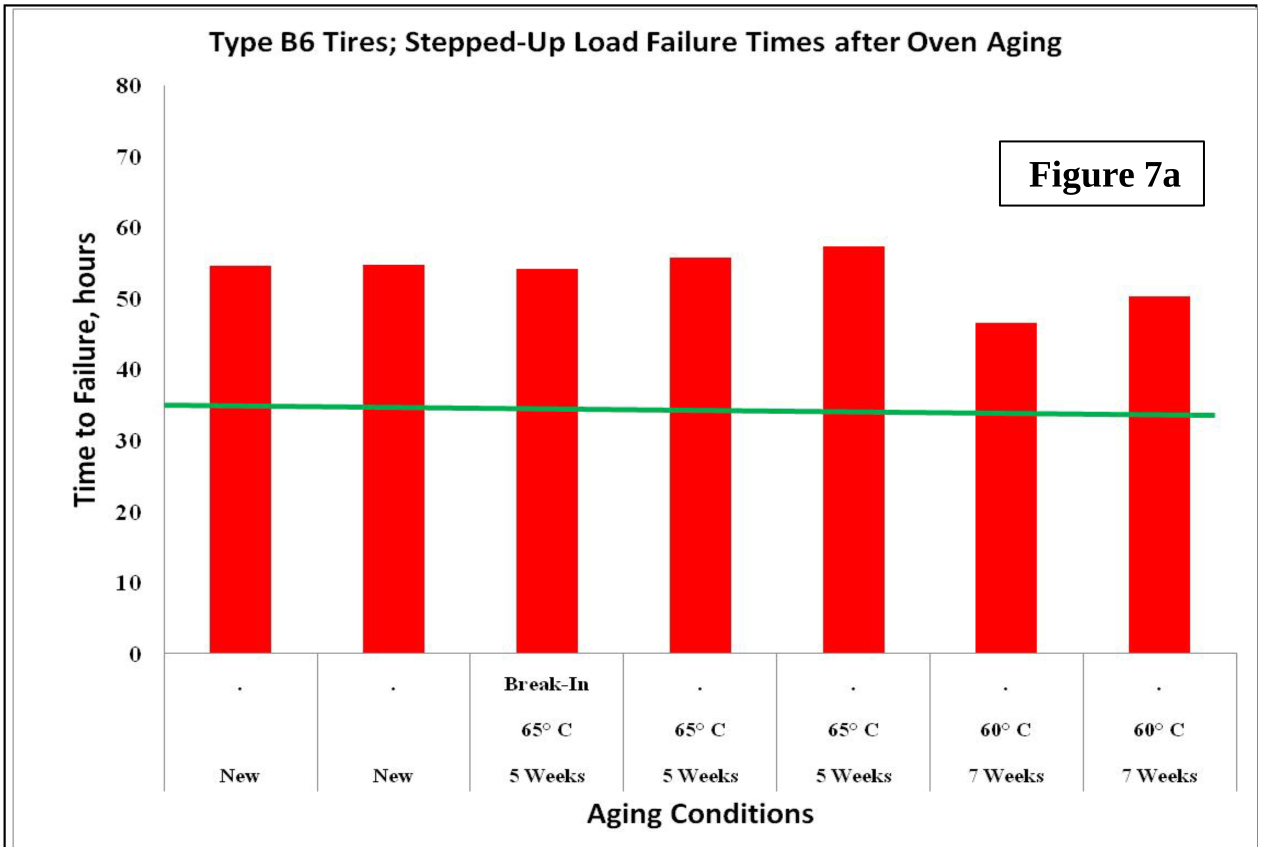
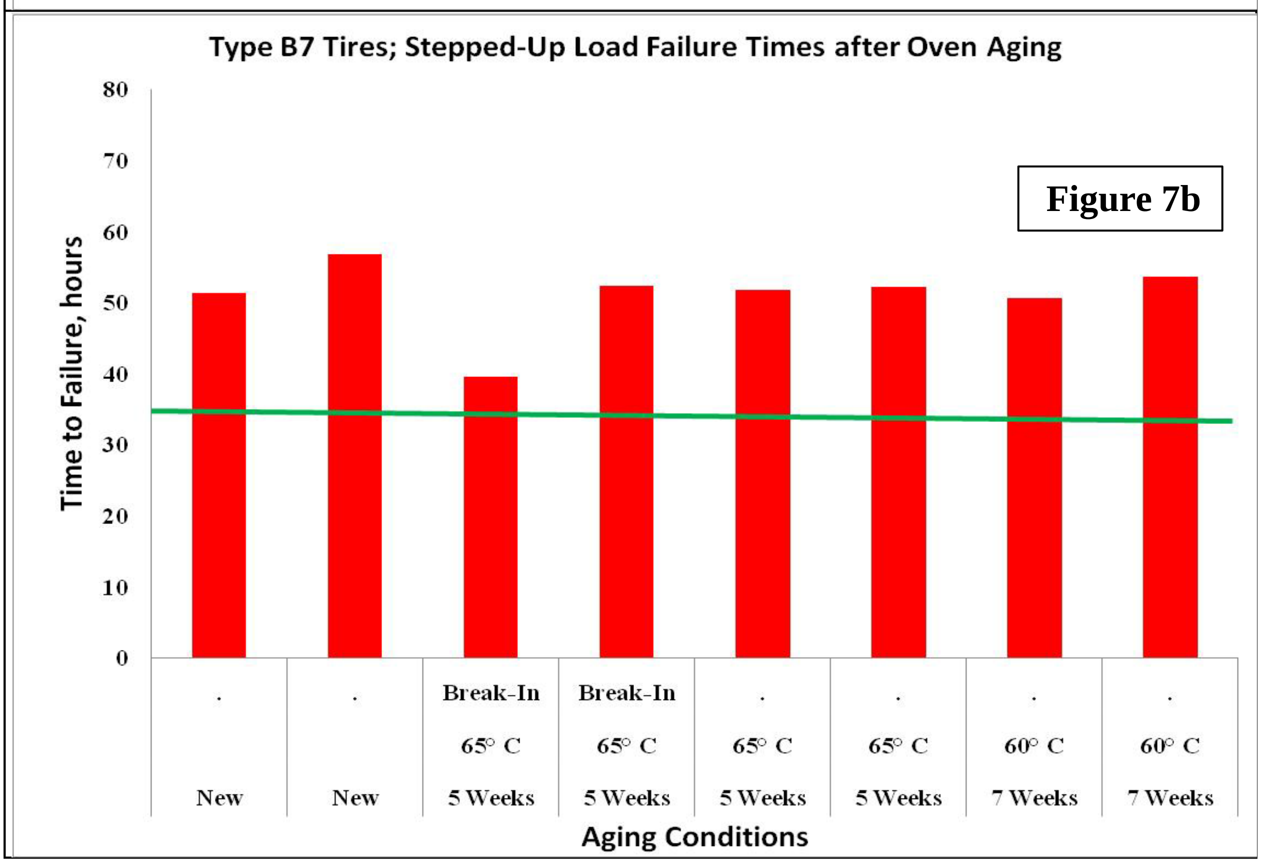
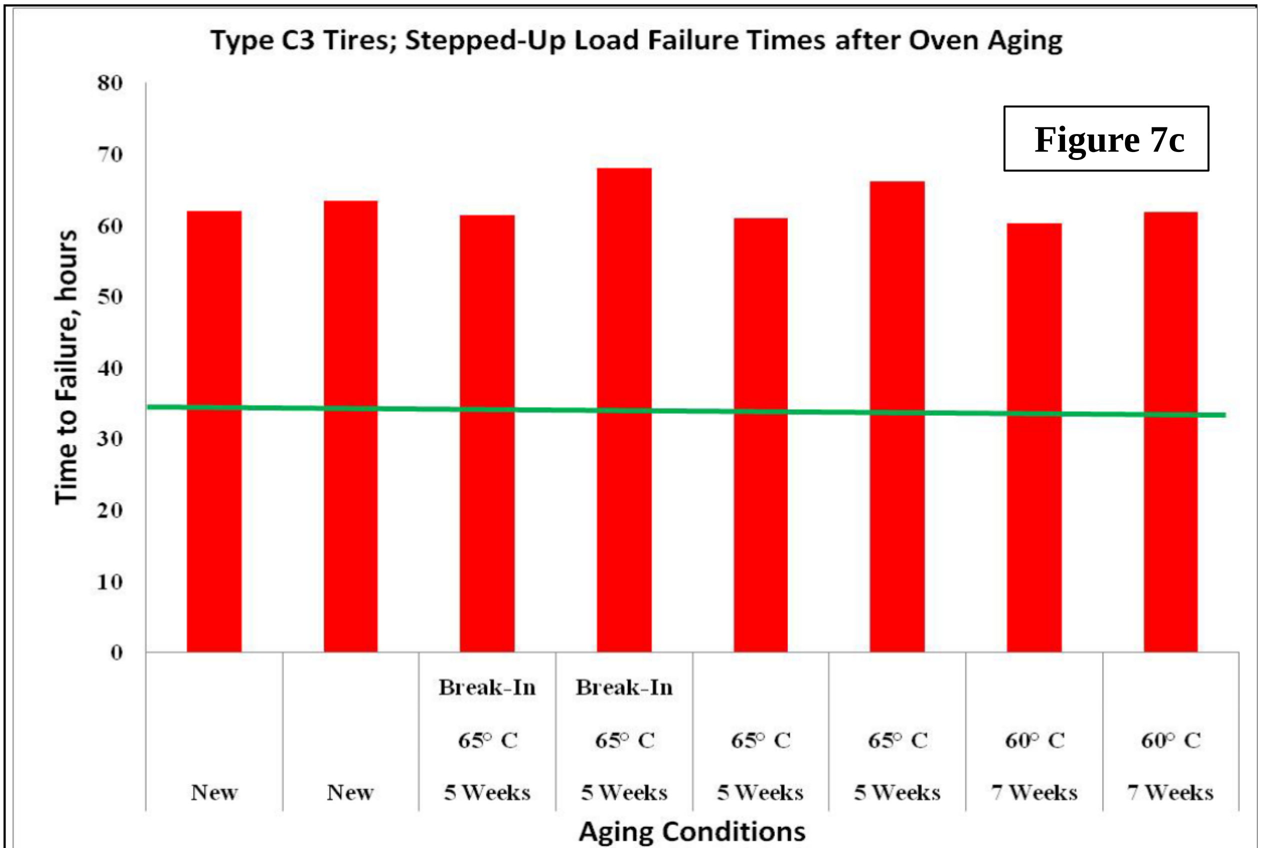


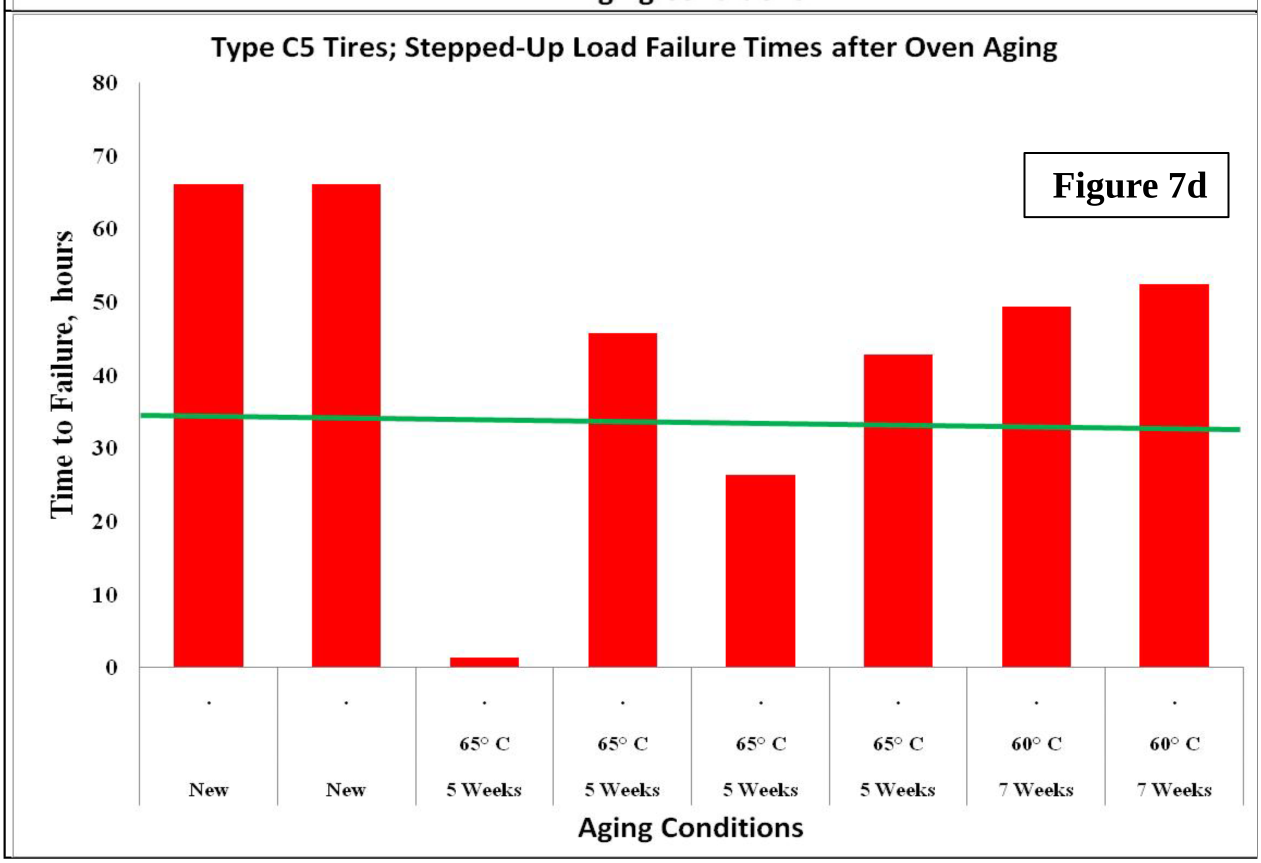
Figure 6. Regression Results for Stepped-Up-Load to Failure Times for Tires in Phoenix Service

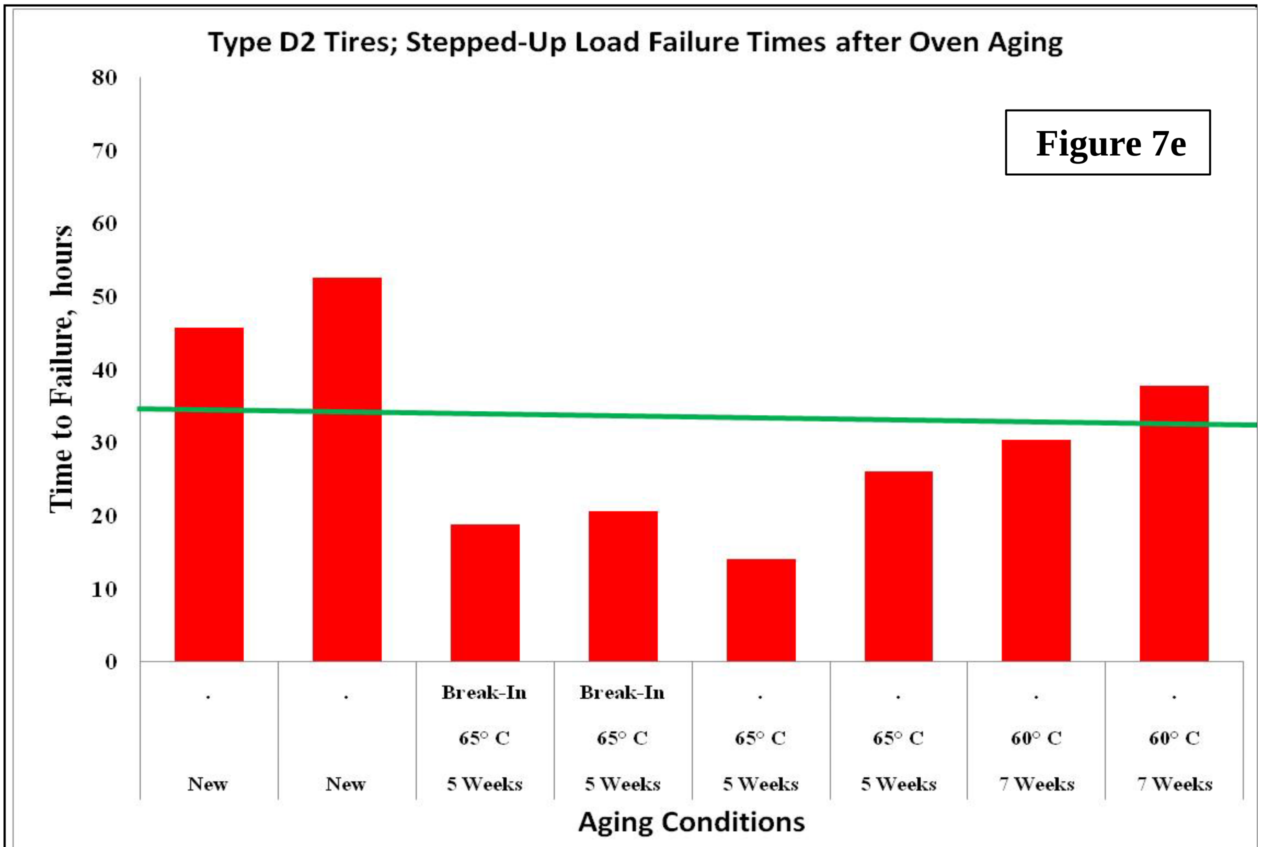
Figure 7, charts a to l which follow contain the roadwheel time-to-failure data for each passenger tire model as new and after oven aging at various conditions. While all of the new tires exhibited failure times beyond 34 hours (shown by the horizontal green line), for the aged tires approximately half of the models ran beyond the 34 hour test time, and the rest failed in times ranging from less than 4 hours to over 30 hours.

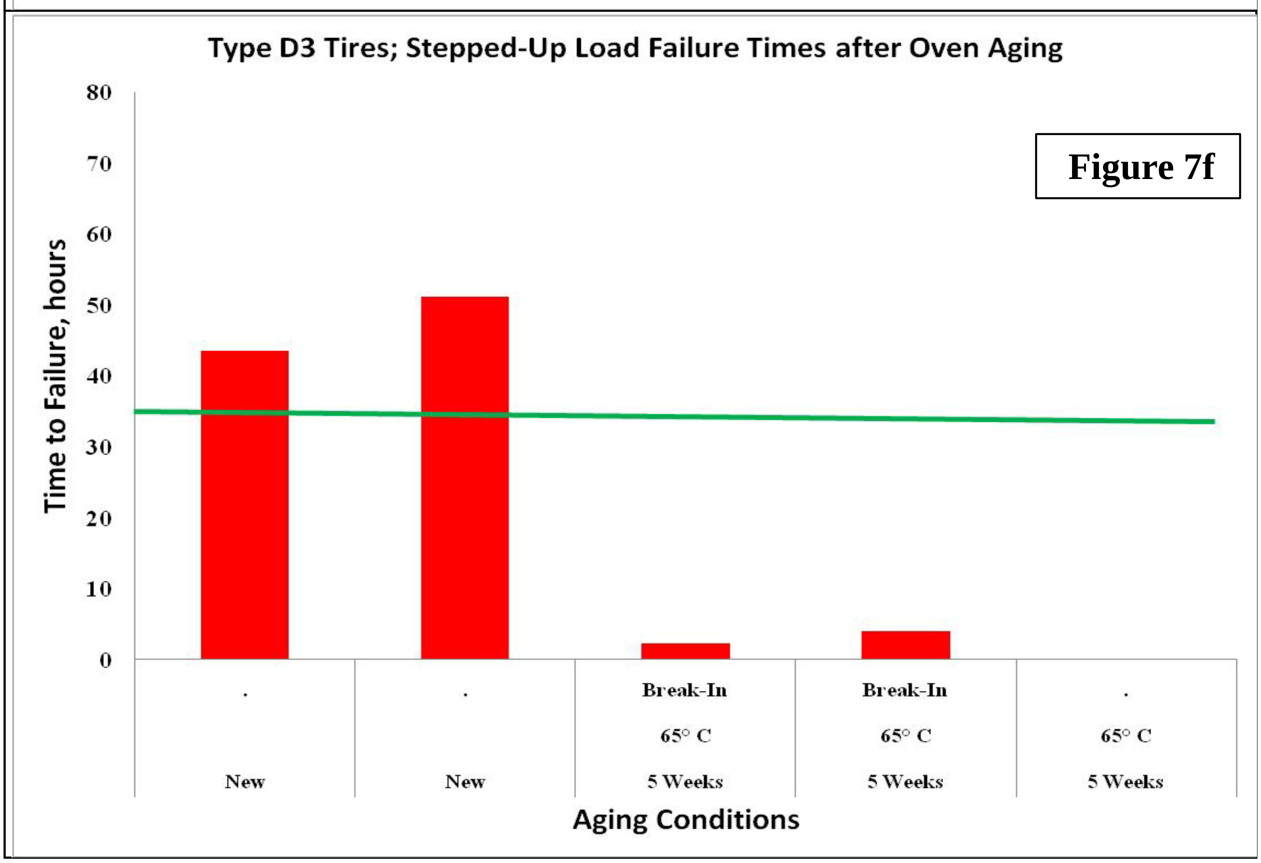

Type B6 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7a
Time to Failure, hours
80
70
60
50
40
30
20
10
0
New
New
Break-In
65° C
5 Weeks
65° C
5 Weeks
65° C
5 Weeks
60° C
7 Weeks
60° C
7 Weeks
Aging Conditions

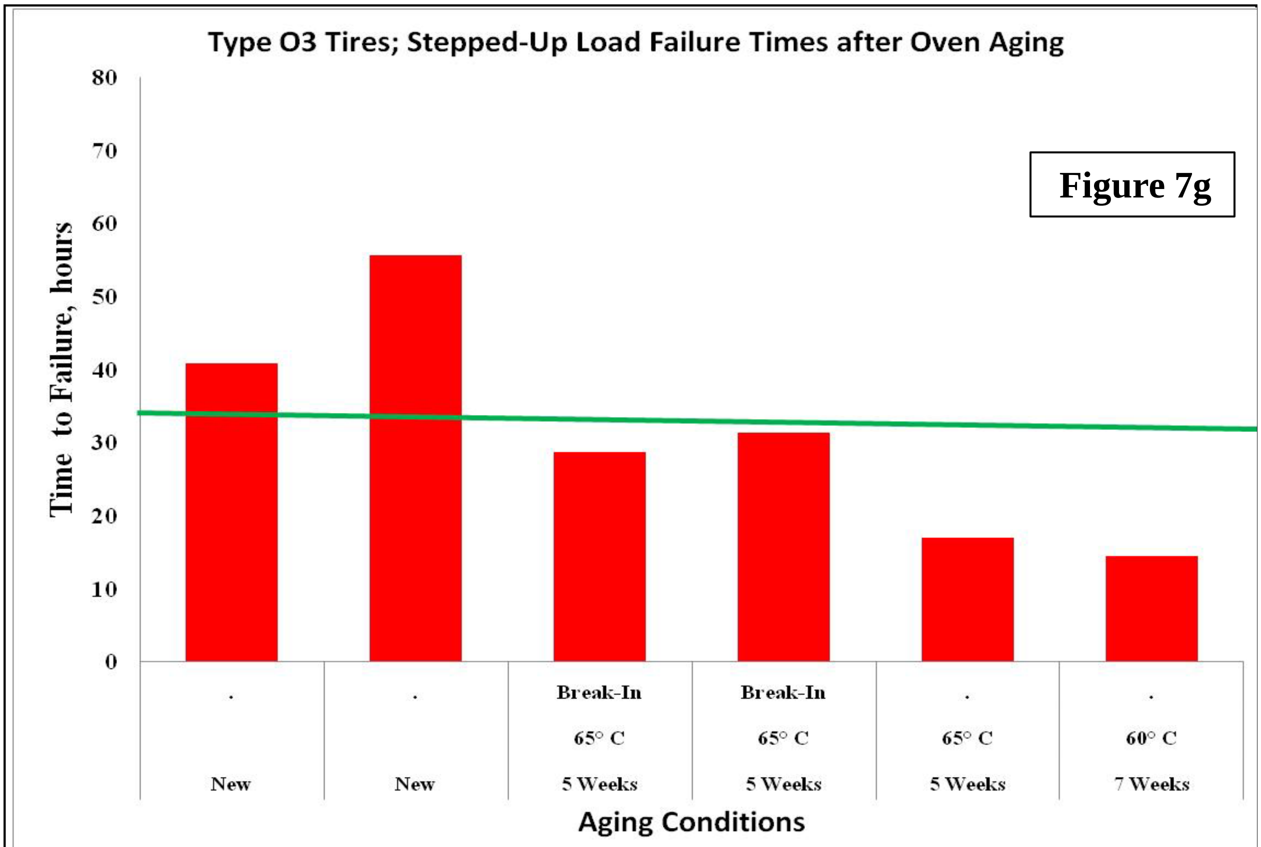

Type B7 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7b
Time to Failure, hours
80
70
60
50
40
30
20
10
0
New
New
Break-In
65° C
5 Weeks
Break-In
65° C
5 Weeks
65° C
5 Weeks
65° C
5 Weeks
60° C
7 Weeks
60° C
7 Weeks
Aging Conditions


Type C3 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7c
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions

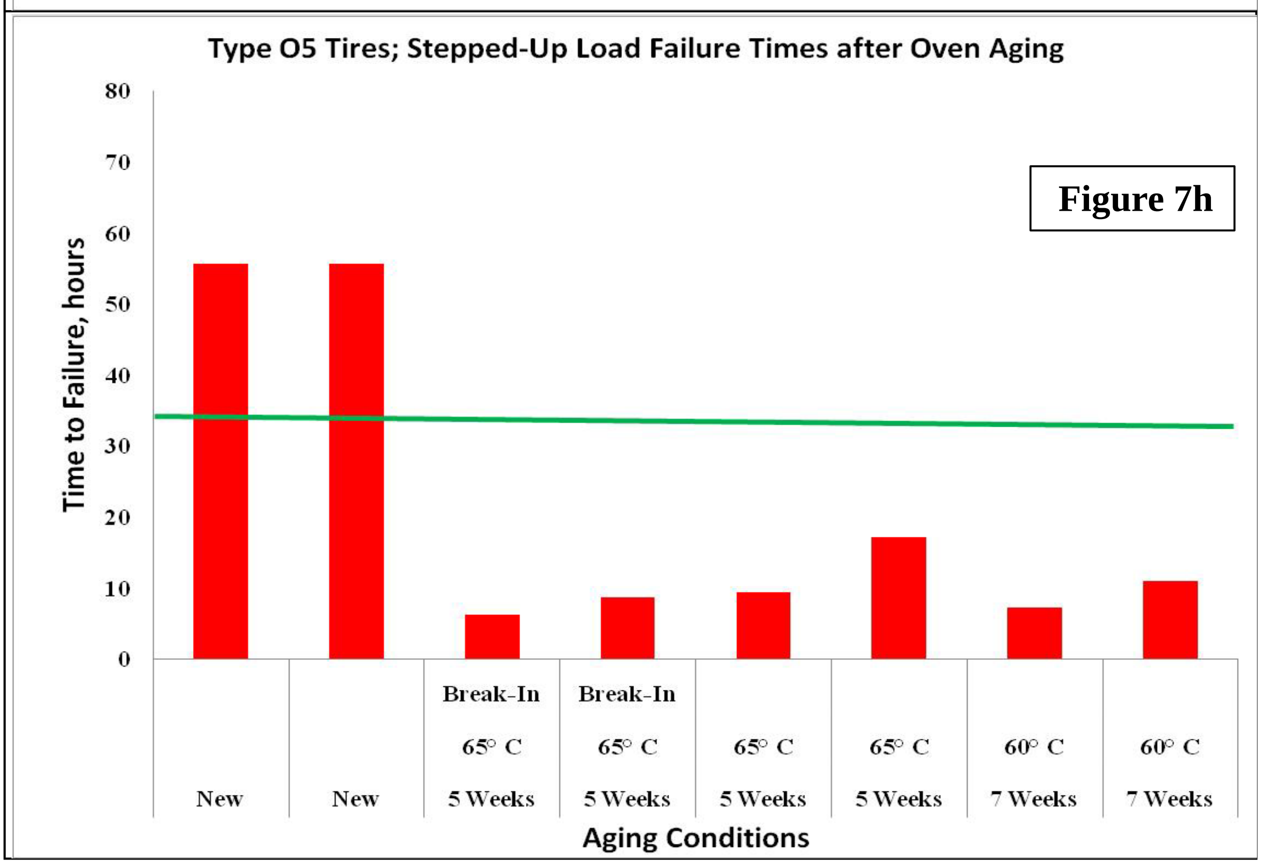

Type C5 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7d
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions


Type D2 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7e
Time to Failure, hours
80
70
60
50
40
30
20
10
0
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions

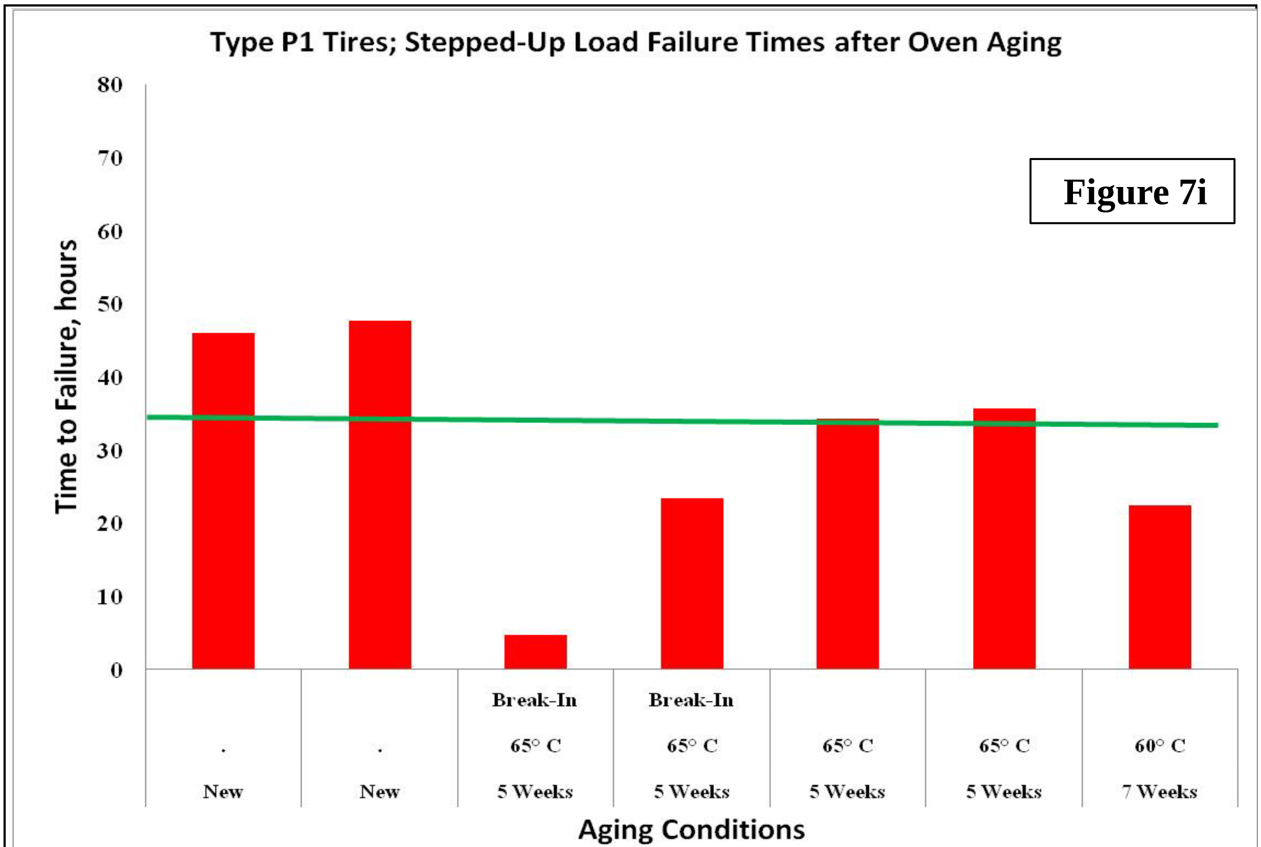

Type D3 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7f
Time to Failure, hours
80
70
60
50
40
30
20
10
0
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
Aging Conditions

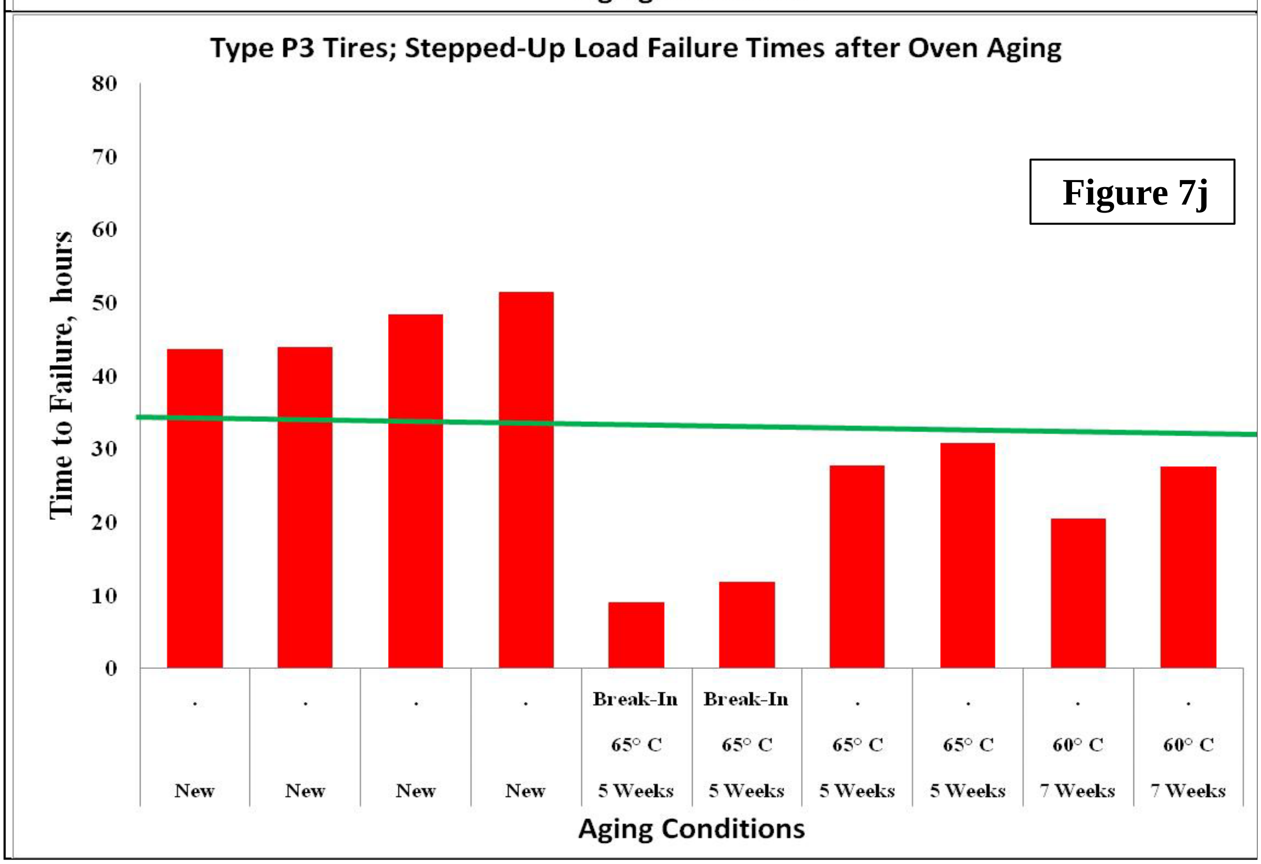


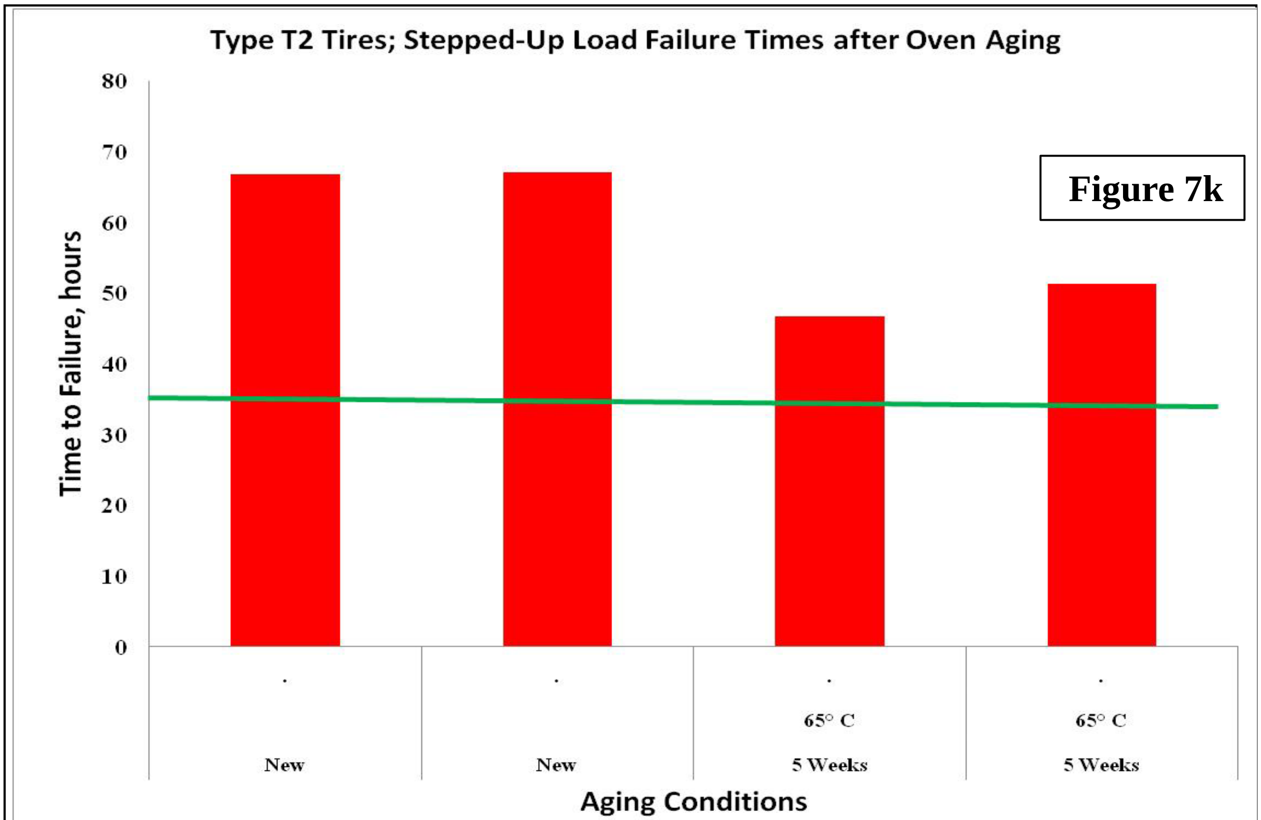
Type O3 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7g
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
Break-In
65° C
5 Weeks
Break-In
65° C
5 Weeks
65° C
5 Weeks
60° C
7 Weeks
Aging Conditions



Type O5 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7h
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
Break-In
65° C
5 Weeks
Break-In
65° C
5 Weeks
65° C
5 Weeks
65° C
5 Weeks
60° C
7 Weeks
60° C
7 Weeks
Aging Conditions


Type P1 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7i
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
Aging Conditions


Type P3 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 7j
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions



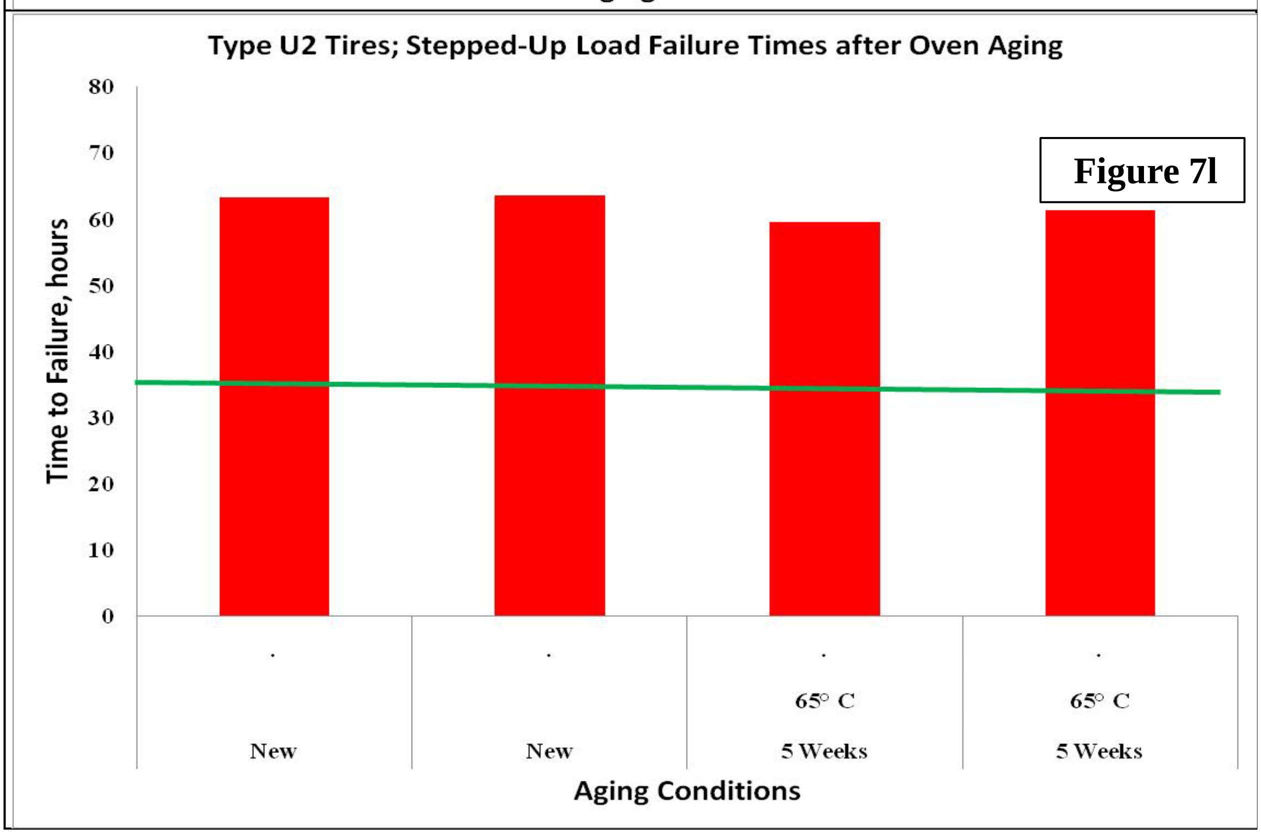


Figure 7. Passenger Tires Tested by Stepped-up-load, New and After Oven Aging

The light truck tire times to failure results are shown in Table 21. The failure modes of thirty-five out of 46 aged light truck tires (76%) exhibiting visible failures in less than 34 hours of roadwheel testing are summarized in Figure 8. Approximately one third of these failures occurred in the belt area, with another 10% taking place in the shoulder area. Failures in the sidewall accounted for 29% of the visible failures in the oven aged tires, with a lesser number of innerliner, bead, tread, and carcass failures. Nine tires (19%) failed by sidewall or innerliner separation during the oven aging process, prior to testing on the roadwheel.

Three tires of the D5 light truck tire model listed in Table 21 were subsequently recalled by their manufacturer in NHTSA Campaign ID Number 07T005000 for the following: "*Summary: The tread can separate from the tire casing. Consequence: A vehicle crash can occur*." Of the three recalled D5 tires, one was a new tire that ran 38.52 hours in the Stepped-Up Load roadwheel test and failed from "*CT+B2D: Complete tread and belt 2 detachment*." The second was a tire broken-in on the roadwheel for 23 hours at 80 km/h (50 mph), oven aged for 5 weeks at 65°C, and then subjected to the Stepped-Up Load roadwheel test. This tire failed in 3.17 hours from *"ILS: Inner Liner Separation."* The third tire had no pre-oven break-in, was oven aged for 7 weeks at 60°C, then subjected to the Stepped-Up Load roadwheel test. This tire failed in 0.65 hours from *"PT+B2D/BEE: Partial Tread and Belt 2 Detachment / Belt Edge Exposed."*

Table 21. Failure Conditions of Light Truck Tire Models
(Failure Times of Less Than 34 Hours Shown in Bold)

Tire Type	Aging Temperature	Weeks in Oven	Break-In	Hours to Failure	Failure Notes	Barcode
B4	New	.	.	56.47	BdTuR/ILF: Bead Turn-up Rupture of Body Ply Cords with Radial Cracking/ Innerliner Failure	2201
B4	New	.	.	54.58	BdTuR/ILF: Bead Turn-up Rupture of Body Ply Cords with Radial Cracking/ Innerliner Failure	2202
B4	65	5	None	54.22	BdTuCr: Bead Turn-up Cracking	2203
B4	65	5	23 hrs	46	PT+B2D/BEE: Partial Tread and Belt 2 Detachment/ Belt Edge Exposed	2206
B4	65	5	23 hrs	34	BEE: Belt Edge Exposed	2207
B4	60	7	None	7.93	PT+B2D/BEE: Partial Tread and Belt 2 Detachment/ Belt Edge Exposed	2209
B4	60	7	None	4.93	ILS: Inner Liner Separation	2210
D4	New	.	.	43.65	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2418
D4	New	.	.	47.33	TShC+BE: Tread Shoulder Chunking with Belts Exposed	2419
D4	65	5	None	5.33	CT+B2D: Complete Tread and Belt 2 Detachment	2420

Tire Type	Aging Temperature	Weeks in Oven	Break-In	Hours to Failure	Failure Notes	Barcode
D4	65	5	None	1.83	CT+B2D: Complete Tread and Belt 2 Detachment	2421
D4	65	5	23 hrs	4	B1P1D/CaR: Belt 1 to Carcass Detachment/Carcass Rupture	2423
D4	65	5	23 hrs	7.93	CT+B2D: Complete Tread and Belt 2 Detachment	2424
D4	60	7	None	0.45	ShSW: Shoulder Swelling	2426
D4	60	7	None	0.62	PT+B2D/B1P1D: Partial Tread and Belt 2 Detachment/Belt 1 to Carcass Detachment	2427
D5[x]	New	.	.	38.52	CT+B2D: Complete Tread and Belt 2 Detachment	2405
D5	New	.	.	39.2	CT+B2D: Complete Tread and Belt 2 Detachment	2406
D5	65	5	None	1.38	B1P1D/CaR: Belt 1 Partial Detachment /Carcass Rupture	2407
D5	65	5	None	1.6	B1P1D: Belt 1 to Carcass Detachment	2408
D5	65	5	23 hrs	0	FIO: Failed in oven at week 5 due to: Innerliner separation (BES/PCD-I)	2410
D5[x]	65	5	23 hrs	3.17	ILS: Inner Liner Separation	2411
D5[x]	60	7	None	0.65	Partial Tread and Belt 2 Detachment / Belt Edge Exposed	2414
D5	60	7	None	0	FIO: Failed in oven at week 7 due to: Tread blister	2415
G2	New	.	.	52.48	Tread Chunking Bead Failure OSS	2114
G2	New	.	.	54.93	TLC	2116
G2	65	5	None	0	FIO: Failed in oven at week 5 due to: Sidewall blister (PCD- TC Plycoat Delamination to Cords)	2118
G2	65	5	23 hrs	0	FIO: Failed in oven at week 2 due to: Sidewall blowout (SwBlister: Blister on sidewall, PCD: Ply Coat Delamination)	2120
G2	65	5	23 hrs	43.78	SwR+DL: Sidewall Rupture with Delamination	2121
G2	60	7	None	57.8	ILS	2123
G2	60	7	None	53.67	BdTuR/BdTuCr: Bead Turn-up	2124

[x] These tires were subsequently recalled by their manufacturer. NHTSA Action Number: EA06021, NHTSA Campaign ID Number: 07T005000, 91,747 tires, http://www-odi.nhtsa.dot.gov/cars/problems/recalls/recallsearch.cfm

Tire Type	Aging Temperature	Weeks in Oven	Break-In	Hours to Failure	Failure Notes	Barcode
					Rupture of Body Ply Cords with Radial Cracking/ Bead Turn-up Cracking	
O1	New	.	.	43.03	TLC: Tread Lug Chunking	2327
O1	New	.	.	50.95	TLC: Tread Lug Chunking	2328
O1	65	5	None	0	FIO: Failed in oven at week 5 due to: Sidewall blister PCD-I Ply Coat Delamination Interface)	2329
O1	65	5	None	34	BdTuCr: Bead Turn-up Cracking	2330
O1	65	5	23 hrs	0	FIO: Failed in oven at week 3 due to: Sidewall blowout (PCD-TC Plycoat Delamination to Cords)	2332
O1	65	5	23 hrs	16.82	SwR+DL: Sidewall Rupture and Delamination	2333
O1	60	7	None	45.97	SwR+DL: Sidewall Rupture with Delamination	2335
O1	60	7	None	41.48	SwR+DL: Sidewall Rupture with Delamination	2336
O2	New	.	.	29	Tread Shoulder Cracking	2340
O2	New	.	.	43.03	SwR+DL TShCr	2341
O2	65	5	None	9	Shoulder Slit	2342
O2	65	5	None	24.7	Sidewall Cracking	2343
O2	65	5	23 hrs	0	FIO: Failed in oven at week 3 due to: Sidewall blisters (PCD- I Ply Coat Delamination Interface)	2346
O2	65	5	23 hrs	4.57	Sidewall Rupture and Delamination / Sidewall Cracking	2347
O2	60	7	None	0	FIO: Failed in oven at week 6 due to: Cracks in bead filler	2349
O2	60	7	None	16.08	Sidewall Rupture	2350
P2	New	.	.	55.22	Tread Chunking	2027
P2	New	.	.	45.47	TShC	2029
P2	65	5	None	33	Sidewall Rupture and Delamination	2030
P2	65	5	None	55.07	SwR+DL	2031
P2	65	5	23 hrs	15.17	Inner Liner Separation	2033
P2	65	5	23 hrs	39.02	BEE PT+B2D	2034
P2	60	7	None	33.93	SwR+DL	2036
P2	60	7	None	38.08	BEL BEE SwR+DL	2037
R2	New	.	.	47.45	PT+B2D	2127
R2	New	.	.	49.08	TLC	2128
R2	65	5	None	19.57	Innerliner Separation/Sidewall Blister	2129

Tire Type	Aging Temperature	Weeks in Oven	Break-In	Hours to Failure	Failure Notes	Barcode
R2	65	5	None	13.67	Shoulder Rupture / Carcass Rupture / Belt Edge Separation	2130
R2	65	5	23 hrs	17.28	Inner Liner Separation	2132
R2	65	5	23 hrs	27	Sidewall Rupture and Delamination	2133
R2	60	7	None	0	FIO: Failed in oven at week 7 due to: Tread blister	2137
R2	60	7	None	25.02	Partial Tread and Belt 2 Detachment / Belt Edge Exposed	2138

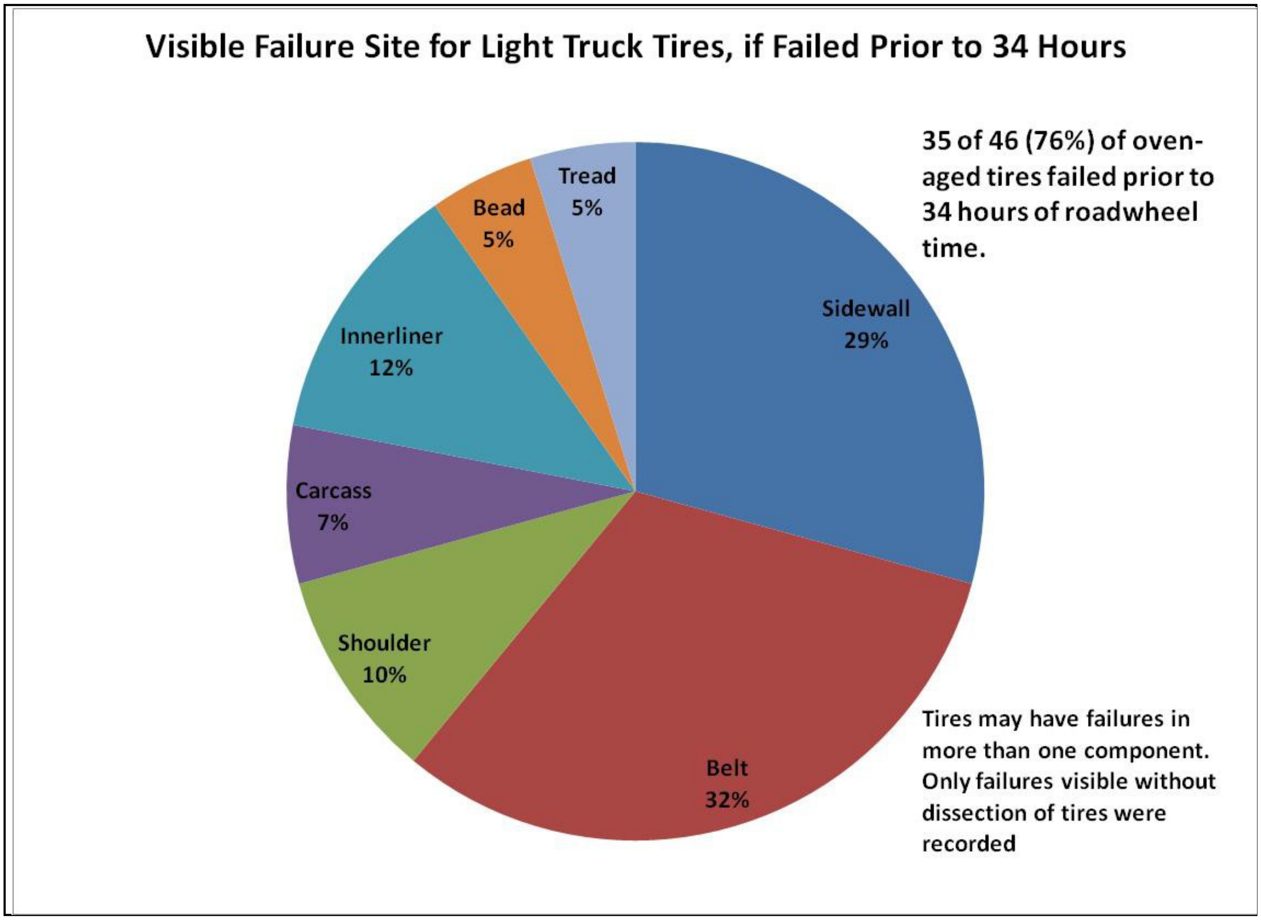
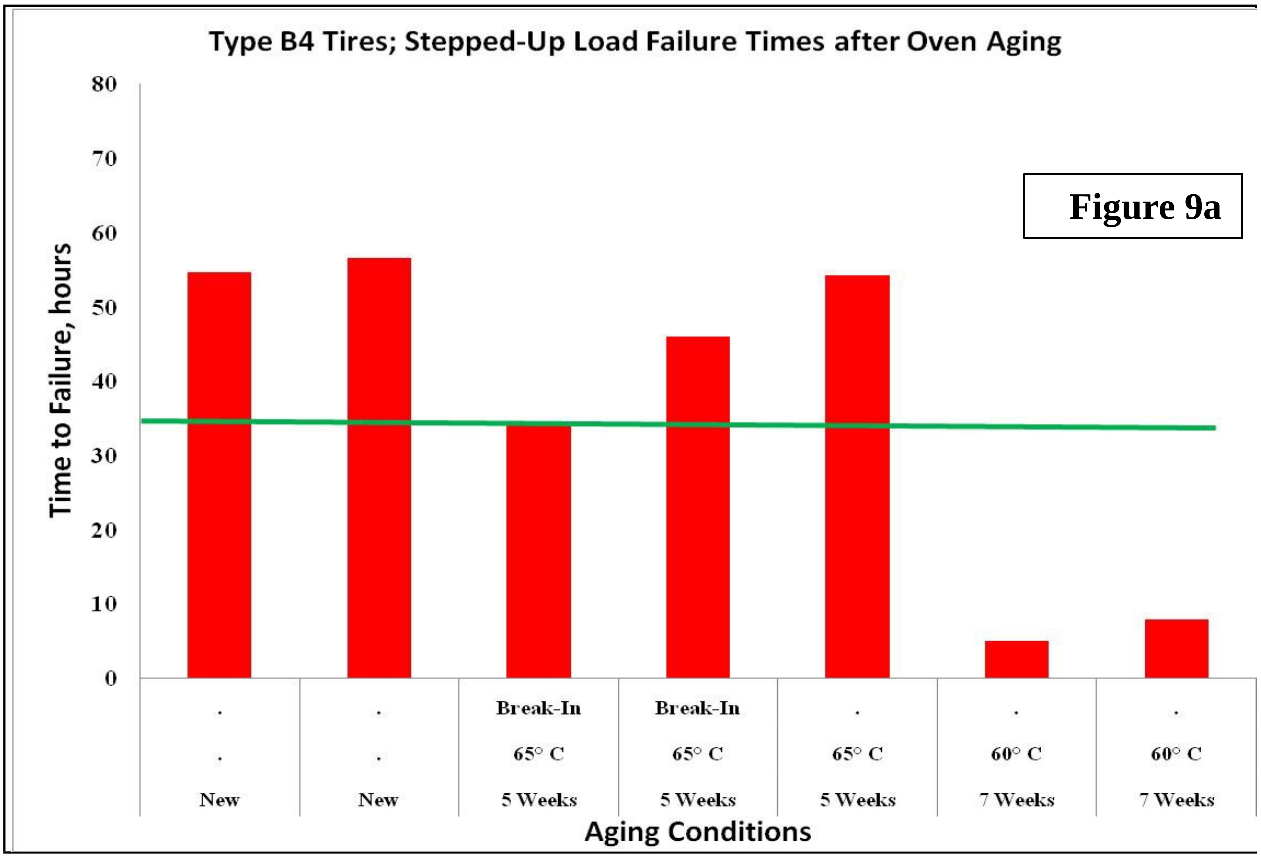
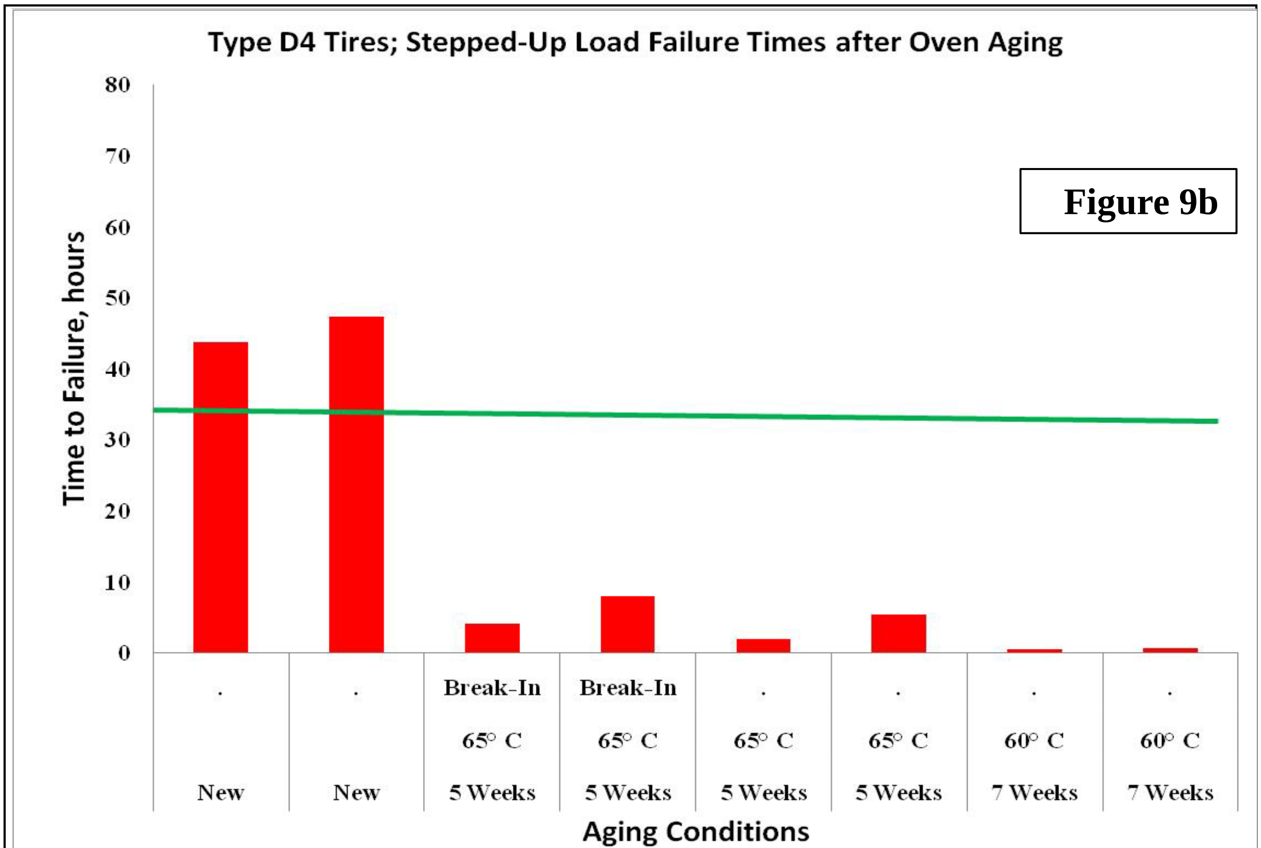
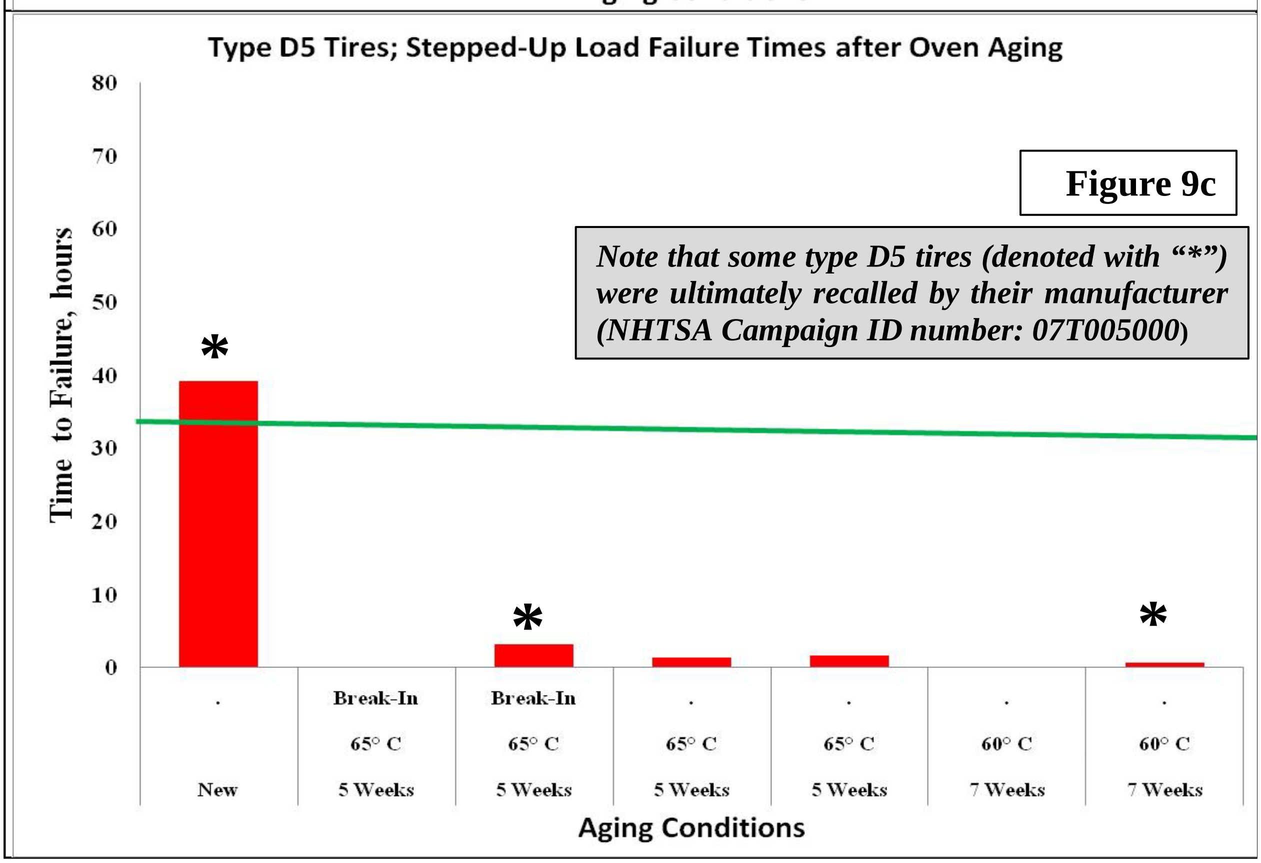


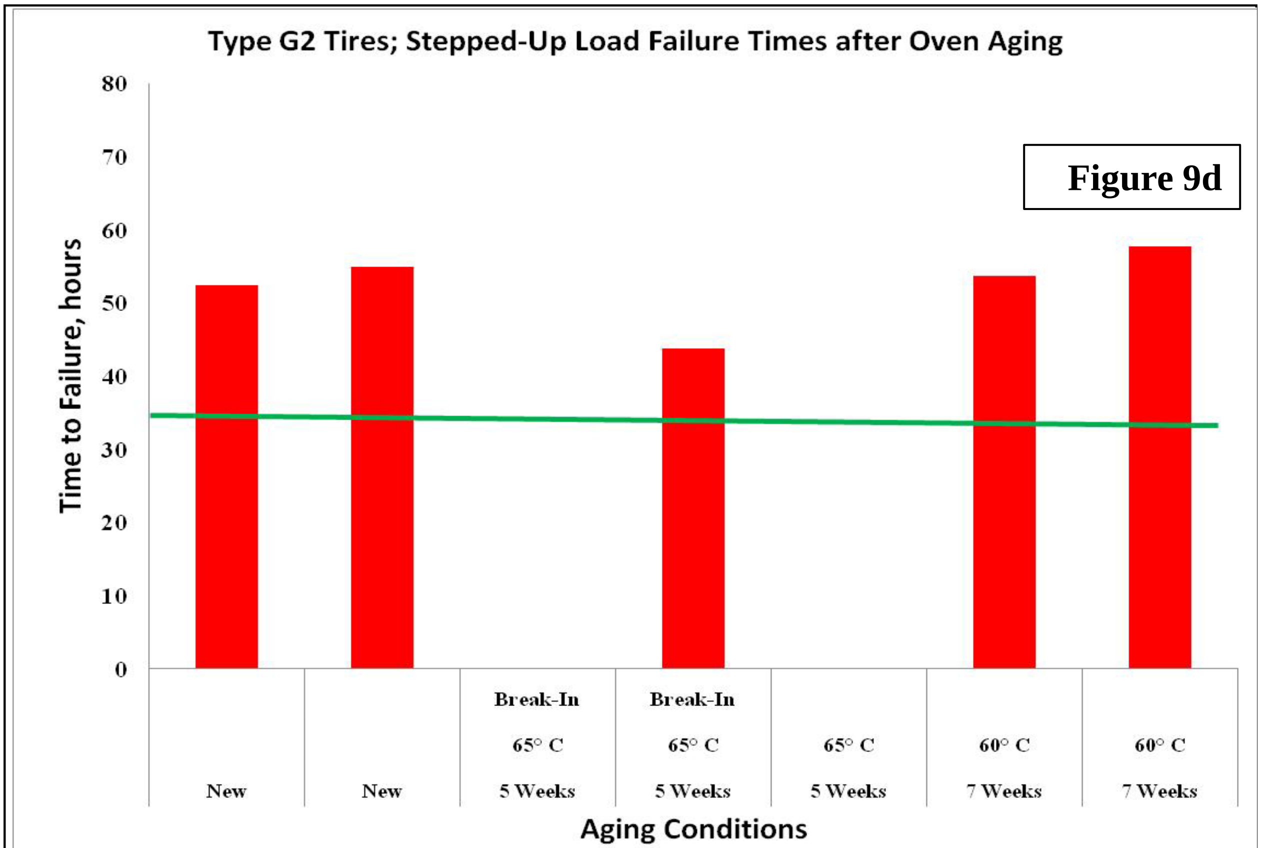
Figure 8. Site of Failure for Light Truck Tires, if Failure Time was Less Than 34 Hours

Figure 9 charts *a* to *l* contain the roadwheel time-to-failure data for each light truck tire model as new and after oven aging at various conditions. Again, tires that failed during the oven aging are indicated in Figure 9 as having zero hours on the post-oven roadwheel test.

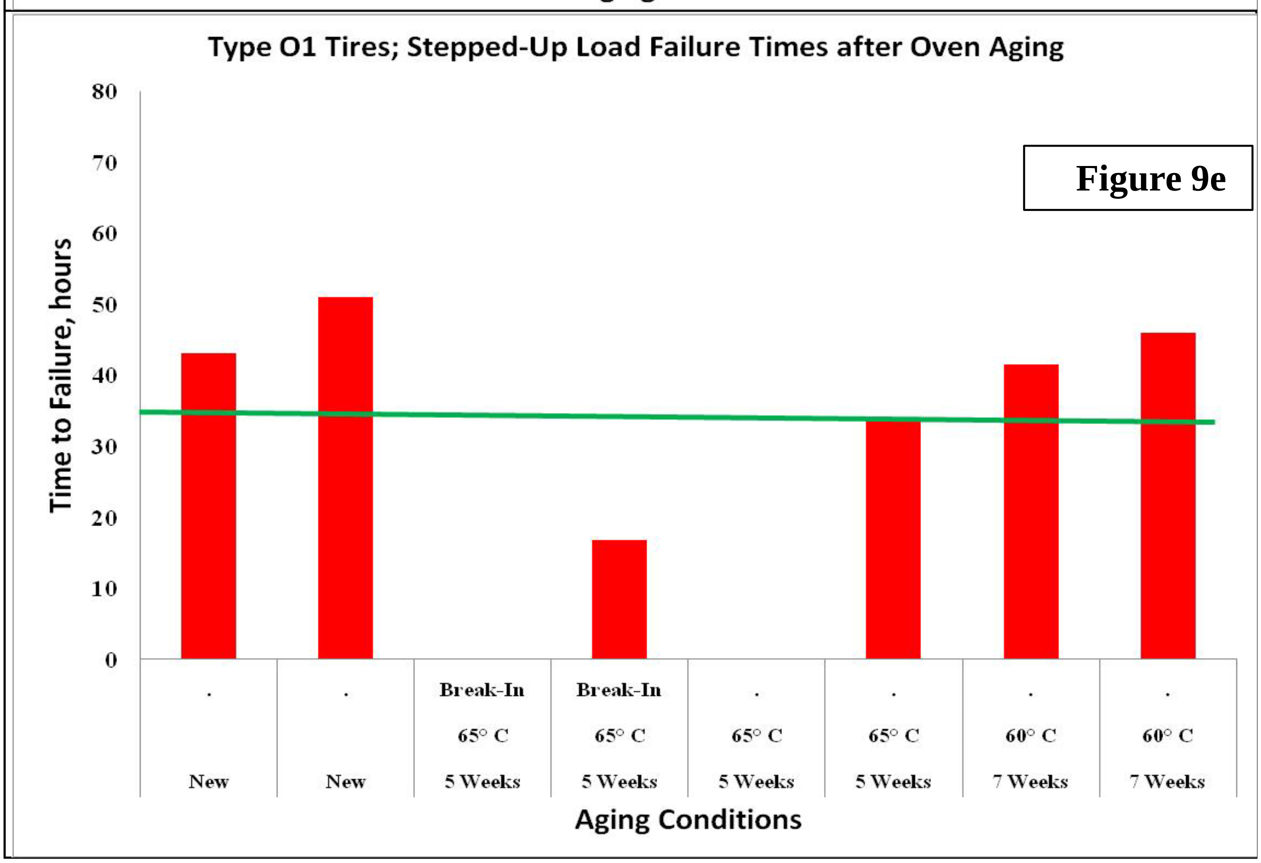



Type D4 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 9b
Time to Failure, hours
80
70
60
50
40
30
20
10
0
.
New
.
New
Break-In
65° C
5 Weeks
Break-In
65° C
5 Weeks
.
65° C
5 Weeks
.
65° C
5 Weeks
.
60° C
7 Weeks
.
60° C
7 Weeks
Aging Conditions

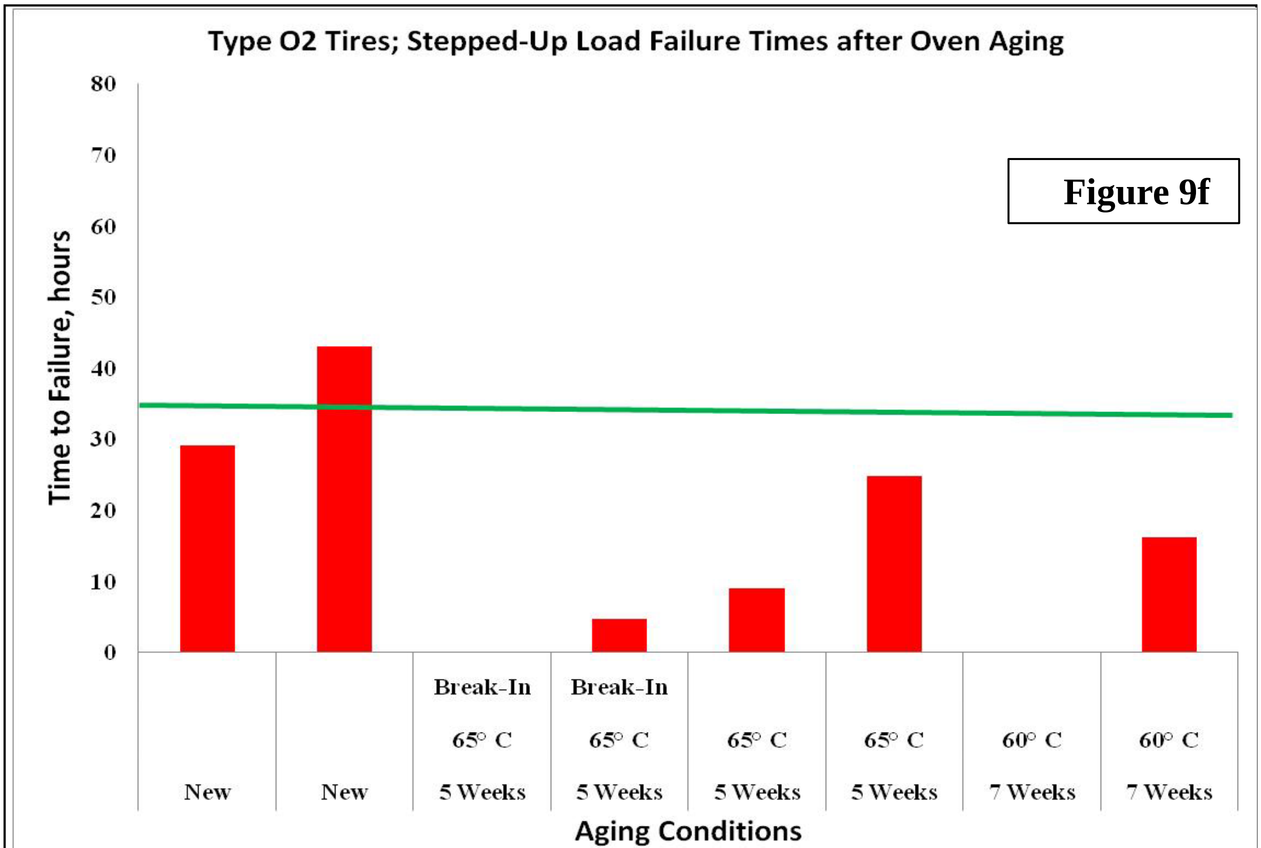

Type D5 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 9c
Note that some type D5 tires (denoted with "*") were ultimately recalled by their manufacturer (NHTSA Campaign ID number: 07T005000)
Time to Failure, hours
80
70
60
50
40
30
20
10
0
*
*
*
.
New
Break-In
65° C
5 Weeks
Break-In
65° C
5 Weeks
.
65° C
5 Weeks
.
65° C
5 Weeks
.
60° C
7 Weeks
.
60° C
7 Weeks
Aging Conditions



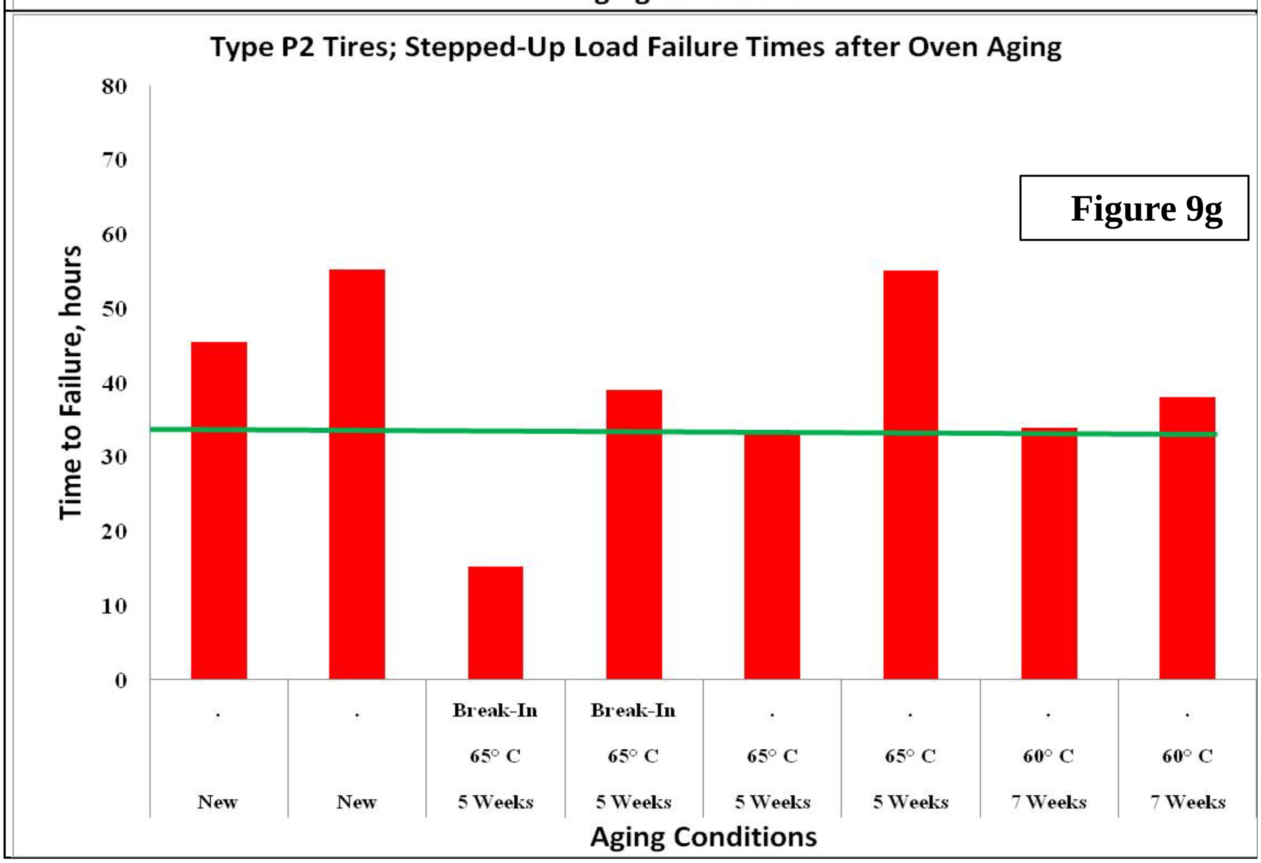
Type G2 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 9d
Time to Failure, hours
80
70
60
50
40
30
20
10
0
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions



Type O1 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 9e
Time to Failure, hours
80
70
60
50
40
30
20
10
0
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions



Type O2 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 9f
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions



Type P2 Tires; Stepped-Up Load Failure Times after Oven Aging
Figure 9g
Time to Failure, hours
0
10
20
30
40
50
60
70
80
New
New
Break-In 65° C 5 Weeks
Break-In 65° C 5 Weeks
65° C 5 Weeks
65° C 5 Weeks
60° C 7 Weeks
60° C 7 Weeks
Aging Conditions

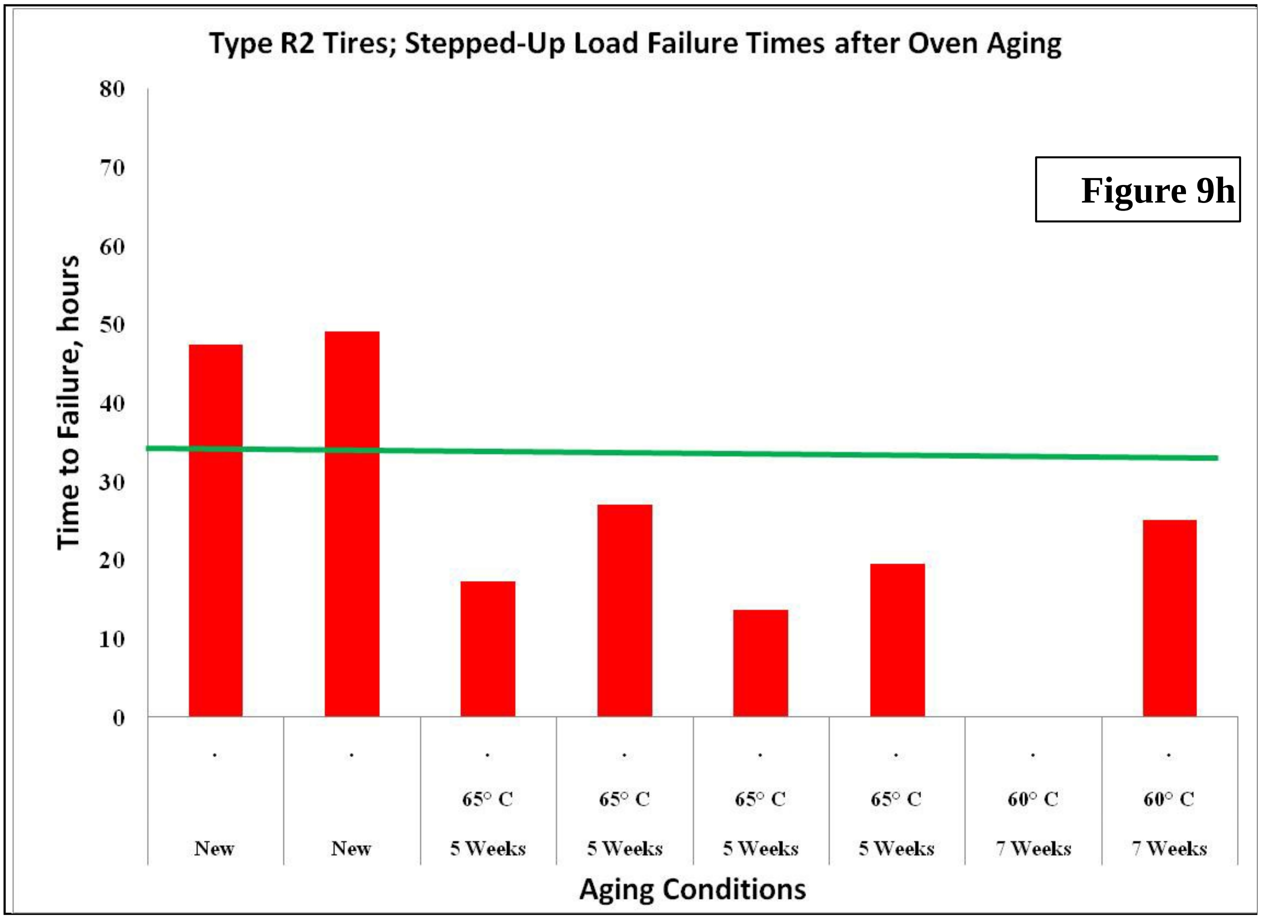


Figure 9. Stepped-up-load Failure Times for Light Truck Tires

3.3 Work During Roadwheel Testing

Data from roadwheel testing of tires retrieved from service in Phoenix indicated that the work to failure decreased with each tire model with increasing age and mileage.(14) Work to failure was defined in Equation 2, referred to as km*maxload in calculations:

Equation 2: Work to Failure

Work to Failure = km*(maximum rated load)

Column 2 of Table 22 shows the service age of a tire from Phoenix expected to fail after 34 hours of roadwheel testing, calculated from the linear regression of roadwheel failure work versus years and distance driven as reported in the Phase 2 work. The average annual mileage of 18,688 km was used for the calculation of estimated years of service to produce an expected time to fail during the §571.139 endurance test. Column 4 shows the calculated oven aging time, in weeks, expected to cause failure in the endurance test for each of the same tire models that were oven aged in Phase 2. The linear relationship between these two sets of values is illustrated in Figure 10. The R^2 of the models used to predict each data point on the chart ranged from 0.65 to 0.95. Even though each individual prediction has low accuracy, the parallel trends of the two aging methods are evident.

Table 22. Predicted Time to Produce Failure During §571.139 Endurance Test

Tire Model	Predicted Phoenix Service to Produce Failure after 34 hrs of Roadwheel Testing, years	Average Temperature of Oven during Aging, °C	Predicted Oven aging to Produce Failure after 34 hrs of Roadwheel Testing, weeks
B	4	63.0	9
C	12.2	63.6	14.6
D	7.2	63.6	7.5
E	1.7	64.5	5.1
H	1.6	63.6	3.6
L	9.2	63.6	15.8

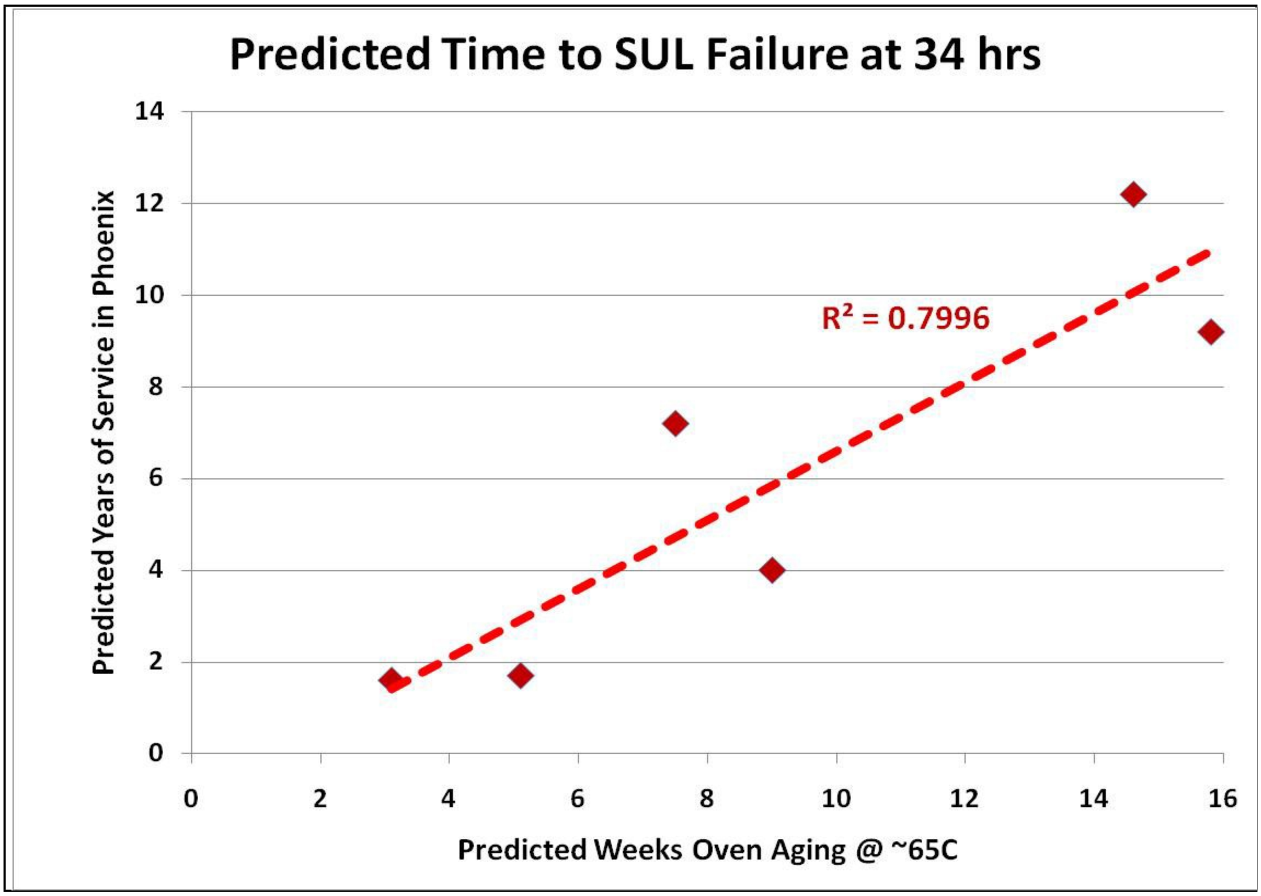


Figure 10. Predicted Time to Produce Failure during §571.139 Endurance Test, Phoenix Service versus Oven Aging

The mean predicted weeks of oven aging required to produce failure at 34 hours of the SUL test (equivalent to the §571.139 Endurance conditions) for each tire model is shown in Table 23. There does not appear to be a clear relationship between the time to failure of the new tires and the rate of loss of ultimate running time with aging. Some tire models with relatively short failure times of the new tires had little change and some with longer running times of the new tires showed a rapid decline with oven aging. This is illustrated in Figure 11 where the dashed line is predicted failure after 5 weeks of oven aging at 60°C to 70°C. While there was not sufficient data for any individual point to be modeled with a high degree of accuracy, the overall trends are evident.

Table 23. Predicted Weeks of Oven aging Necessary to Produce Failure during §571.139 Endurance Test

Tire Model	Correlation Coefficient, R	Average Work until Failure for New Tire, km*max load	Reduction in Work per Week of Oven aging, km*max load	Average Temperature of Oven during Aging, °C	Predicted Oven aging to Produce Failure after 34 hrs of Roadwheel Testing, weeks
B	-0.79	5628	-188	63.0	9.0
C	-0.91	10100	-420	63.6	14.6
D	-0.89	6909	-396	63.6	7.5
E	-0.87	6421	-487	64.5	5.1
H	-0.94	5524	-479	63.6	3.1
L	-0.85	8231	-182	63.6	>15
B4	-0.75	8175	-768	63.0	5.5
B6	-0.33	7466	-90	63.0	>15
B7	-0.22	7042	-53	63.3	>15
B8	-0.66	8044	-688	65.0	6.0
B9	-0.50	6957	-15	65.0	>15
C3	-0.41	9058	-13	63.3	>15
C5	-0.59	8638	-616	63.3	7.7
C7	-0.61	8463	-55	65.0	>15
C8	-0.69	10732	-348	65.0	>15
D2	-0.71	5706	-415	63.3	4.3
D3	-0.96	5885	-980	65.0	2.0
D4	-0.96	5421	-819	63.3	1.9
D5	-0.95	4430	-684	63.3	0.8
G2	-0.51	5911	-175	63.0	11.3
H3	-0.97	8375	-1270	65.0	3.5
M10	NA	4860	-594	65.0	1.6
O1	-0.33	4933	-267	63.3	3.8
O2	-0.84	4198	-492	63.3	0.6
O3	-0.78	6234	-568	63.8	4.1
O5	-0.97	7055	-972	63.3	3.3
P1	-0.84	5772	-470	64.0	3.9
P2	-0.53	6431	-311	63.3	8.1
P3	-0.88	5638	-524	63.8	3.2
R2	-0.85	6024	-655	63.3	3.2
S1	-0.98	7929	-1167	65.0	3.5
T2	-0.99	9700	-707	65.0	8.2
U2	-0.92	8920	-124	65.0	>15

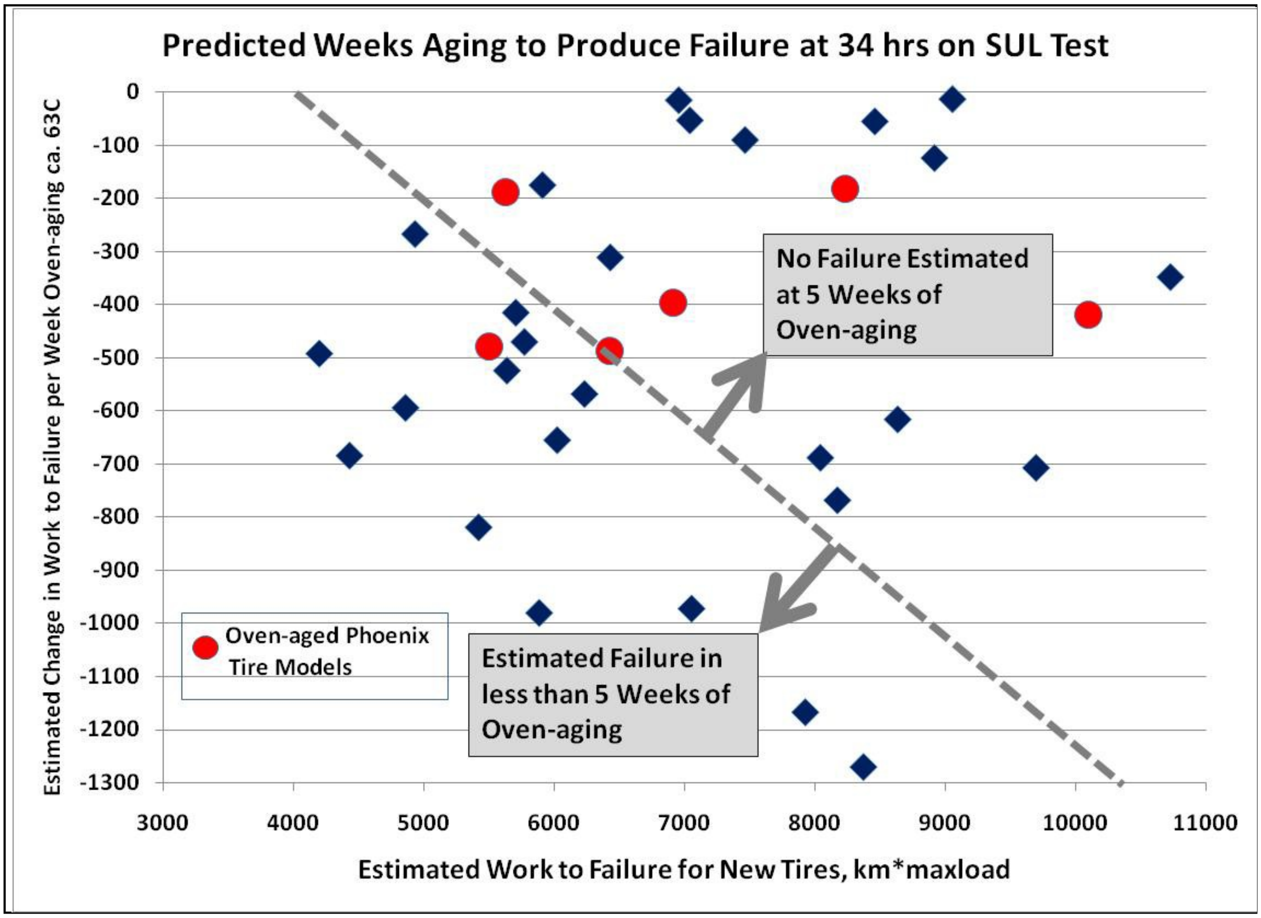


Figure 11. Estimated Change in Work to Failure upon Oven aging versus Work to Failure of New Tires

4.0 SUMMARY AND CONCLUSIONS

The performance tests in §571.139 do not evaluate the structural durability of a tire after it has experienced long-term material property degradation under cyclic fatigue. At question is whether the thermo-oxidative degradation and fatigue cracking of internal rubber components (observed in tires retrieved from service) contribute to a decrease in a tire's resistance to operational conditions. The first goal of tire aging research was to develop a better understanding of service-related tire degradation over time. Phase 1 of this project addressed this goal. The research shows that there are two mechanisms operating to produce changes in tire properties, particularly in the critical belt-edge region. First is degradation of the rubber compound and material interfaces due to the effects of heat and reaction with oxygen *i.e.*, thermo-oxidative aging. Second is cyclic fatigue during tire deformation, which can cause cracks and separations.

Phase 2 of the project focused on developing a laboratory based accelerated test that simulates in-service tire aging. The physical and chemical properties of the belt coat stocks and the remaining structural durability of the aged tires were compared to the six tire models previously evaluated after long-term service in Phoenix. The most effective method was oven aging, in which the tire is inflated using a 50% nitrogen and 50% oxygen mixture (compared to 21% oxygen in dry air), and heated in an oven for several weeks to accelerate chemical reactions and material property changes. The material and chemical properties of critical belt rubber compounds were measured for new tires and for tires of the same model after aging.

Results of the tests on laboratory aged tires closely mimicked those of tires from long term service in Phoenix. Increases in hardness, modulus, cross-link density, and oxygen content and decreases in tensile strength, ultimate elongation, peel adhesion, and flex properties occurred consistent with thermo-oxidative aging. A stepped-up-load test was used to compare the structural integrity of oven aged tires to that of new tires. Oven aging for 3 weeks caused no significant decreases in structural integrity. However, oven aging tires for 6 weeks at 60°C to 70°C decreased the running time on the stepped-up-load test comparable to one to three years of service in Phoenix, while oven aging for 8 weeks at 60°C to 70°C was similar to 5 years of service.

Phase 3 of the research compared selected physical and chemical properties for ten passenger and six light truck tire models oven aged for 10 weeks at 60°C or 8 weeks at 65°C while inflated with a mixture of 50% N_2 / 50% O_2 gas, to the properties of new tires of the same model. The residual integrity of twelve passenger and eight light truck tires were measured using a stepped-up-load test to structural failure after aging for 7 weeks at 60°C, or 5 weeks at 65°C.

The effect of a 23-hour break-in cycle on a 1.707 m roadwheel at 80 km/h prior to oven aging was also investigated.

With no in service tires available for comparison, properties of the tires retrieved from service in Phoenix were compared against the laboratory aged tire values. The physical properties of all tire models showed the same changes as the tires that were investigated in service in Phases 1 and 2. Specifically, the indentation modulus of the wire-coat compounds and shoulder area of the tire increased during aging to levels greater than the average values of with 3 years of service in Phoenix. The modulus of the wire coat compounds, at all levels of strain, increased to levels greater than tires with 3 years of service in Phoenix. The tensile strength and ultimate elongation decreased to values less than the retained values from tires with 3 years of service in Phoenix.

Researchers applied two methods to estimate the rate of oxidation. The first method used the work of Savante Arrhenius from the late 19^{th} century to estimate the rate of oxidation. Arrhenius showed the rate of a chemical reaction was exponentially related to the temperature. Using published values for the activation energy of the rubber compound, researchers calculated that the oxidation reaction in the natural rubber wire-coat compounds of tires aged for 10 weeks at 60°C, or 8 weeks at 65°C, was approximately equivalent to service in Phoenix of 4.8 and 6.5 years, respectively. This result corresponds to aging studies conducted at Ford Motor Company which estimated that aging for 8 weeks at 65°C produces physical properties in tires approximately equivalent to that of 5.5 years of service in Phoenix.

Second, Ahagon and co-workers showed that the slope of the plot of log(modulus @ 100% elongation) versus log(ultimate elongation) correlates to the mechanistic type of aging. The wire-coat compounds of the oven aged tires had slopes near -0.75, corresponding to Type 1 oxidative aging. Measurements of the fixed oxygen level of the wire-coat compound indicated that the amount of oxygen chemically combined with the rubber increased during oven aging by 120% to 175%, confirming that reaction with oxygen was a major factor in the property changes during oven exposure.

Tires oven aged for 7 weeks at 60°C, or 5 weeks at 65°C, were tested on a 1.707 m roadwheel using the stepped-up-load test to structural failure used in Phase 2 testing. Aging conditions were calculated using the Arrhenius equation to be approximately equal to 3.4 and 4.0 years of service in Phoenix, respectively.

At failure times of less than 34 hours, the load on the tire was equal to or less than its rated load, therefore the stresses on individual components could have been experienced in normal service conditions. Twenty-eight of 57 aged passenger tires (49%) exhibited visible failures at times less than 34 hours. Approximately 2/3 of these failures occurred in the belt area, with another 22% of failures taking place in the shoulder area. Over 90% of failures that consumers reported to NHTSA happened in the belt and shoulder area. Thirty-five of 46 aged light truck tires (76%) exhibited visible failure in less than 34 hours of roadwheel testing. Approximately one-third of these failures occurred in the belt area, with another 10% of failures taking place in the shoulder area. Notably, nine light truck tires (19%) failed by sidewall or innerliner separation during the oven aging process, prior to testing on the roadwheel.

During Phase 2 testing, the modulus in the shoulder area of certain tires increased during oven aging even though the modulus decreased during service in Phoenix. It was found that a break-in cycle of 24 hours at 120 km/h prior to oven aging was necessary to match the modulus of oven-aged tires to that of tires in service containing resin reinforcement. In this study, a less severe break-in of 23 hours at 80 km/h was also investigated. For tire type G2 without the roadwheel break-in, the modulus increased by nearly 75% after aging for 8 weeks at 65°C. However, when that tire model was run on a roadwheel prior to oven aging, the modulus of the shoulder after oven exposure was slightly less than that of the new tire.

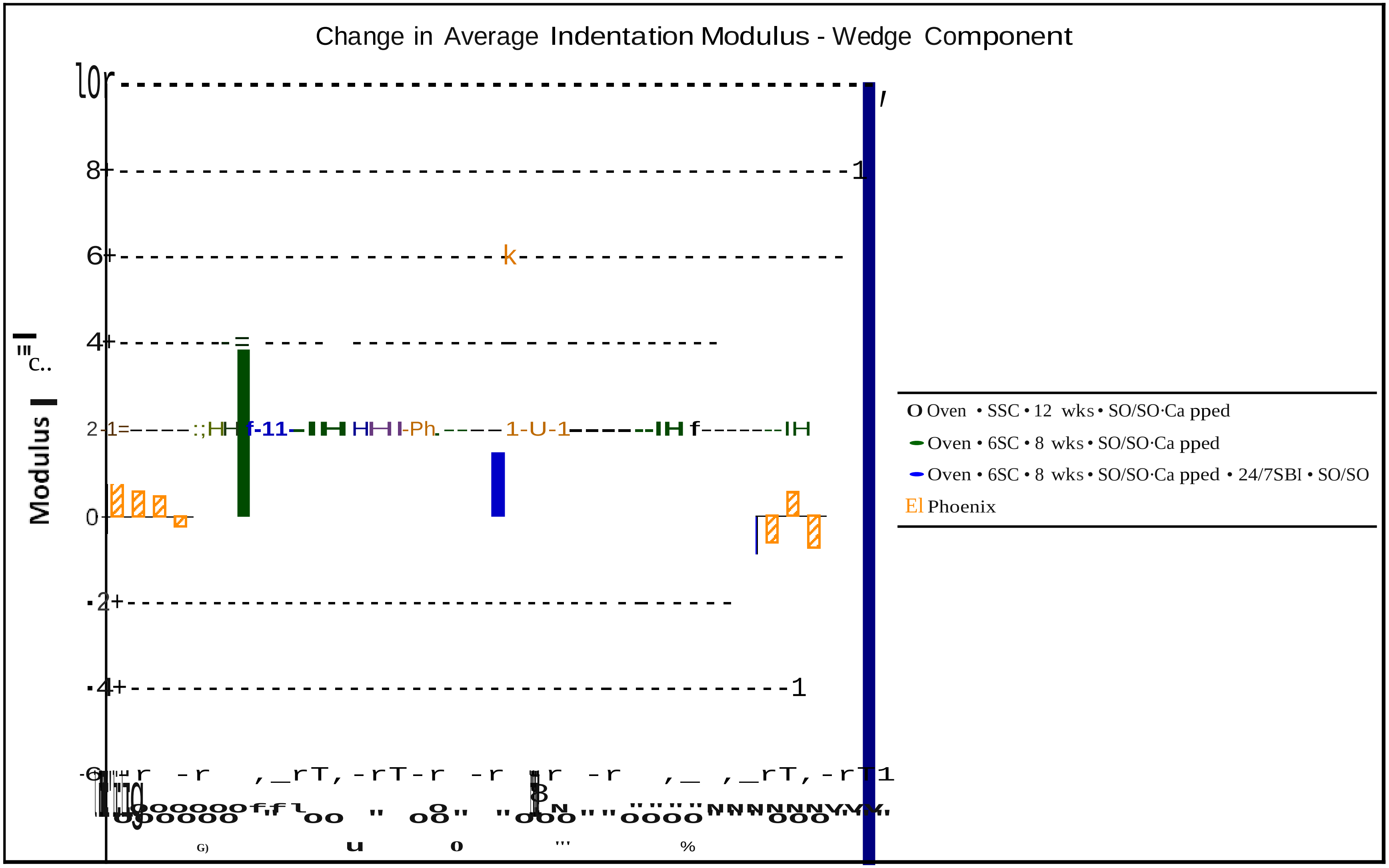
Average failure times were slightly lower for those tires exposed to a break-in cycle. These differences were not statistically significant at a 95% confidence level. For light truck tires the average times were 18 hours without a break-in and 16 hours after a break-in. For passenger tires the averages were 33 hours without a break-in and 26 hours after a break-in.

Based on measured changes in material properties, oven aging tires at 60°C to 70°C while inflated with a mixture of 50% N_2/50% O_2 gas produces thermo-oxidative aging effects qualitatively similar to that found in tires after long-term service in Phoenix. When measured as a percentage of new tire properties, all properties were within the range of values found for the Phase 1 and Phase 2 work. For certain tires, achieving the modulus found during service requires a break-in cycle prior to oven aging, which correlates to the use of thermoset reinforcing resin in the rubber compounds.

Tires oven aged for 7 weeks at 60°C or 5 weeks at 65°C (calculated to be equivalent to 3.5 to 4.5 years of Phoenix service) failed in the §571.139 Endurance test in a significantly shorter time than that of new tires. These values were also consistent with values found in the Phase 1 and Phase 2 testing. Prior to aging, only one out of the 41 (2.4%) of the new, un-aged tires failed prior to the completion of the 100% load step of the §571.139 endurance test method. After aging 49% of passenger tires and 76% of light truck tires failed prior to the completion of the 100% load step.

The oven aging and roadwheel test method evaluated in Phase 3 was shown to be a valid accelerated service life test for tires to evaluate relative risk of failures in later service. An oven test temperature of 65°C was found to be as effective as 60°C in replicating the material properties and roadwheel performance of tires retrieved from service in Phoenix, with the 65°C temperature achieving similar results in a shorter time and thus at lower cost. If the current oven aging procedure was conducted for a shorter period of time, fewer tires would fail to exceed the §571.139 endurance test requirements. Post-test analysis indicated that utilizing a 23-hour pre-test roadwheel break-in aided in matching the material properties of in-service tires, but impacted the final roadwheel running time of the oven aged tires. The duration of this break-in should be reduced in future development efforts.

APPENDIX 1. INDENTATION MODULUS PROFILES FOR THE WEDGE AREA COMPOUNDS-SIX PHOENIX TIRE MODELS



APPENDIX 2. TIRE FAILURES DURING OVEN AGING

Tire Barcodes: 2118, 2120, 2122, 2125, 2134, 2137, 2208, 2329, 2332, 2334, 2346, 2349, 2381, 2409, 2410, 2413, 2415

N2118 – G2 PJ0RY5HV3205 LT235/85R16

Test: HYB8_65_II_R oven age at 65C

End of Test: 5 weeks in oven at 65C

Finding: PCD-TC Plycoat Delamination to Cords OSS

N2120 - G2 PJ0RY5HV3205 LT235/85R16

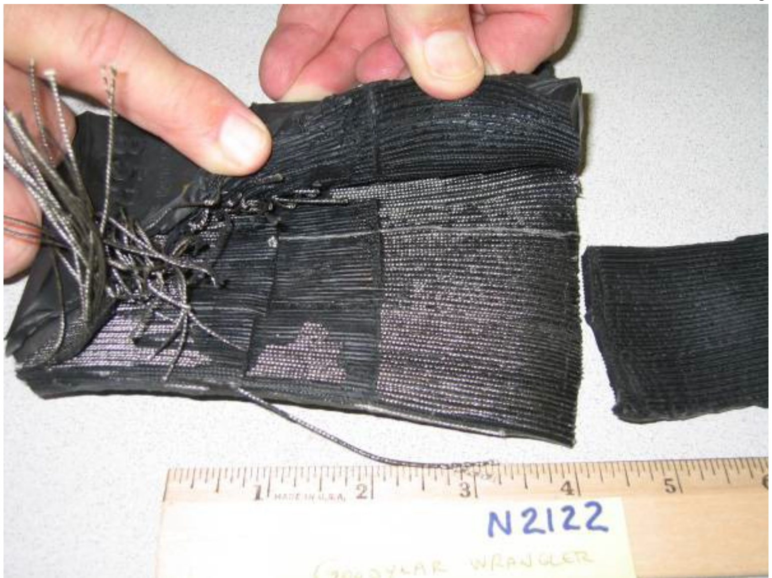
Test:HYB8_65_II_BI_23_R Oven 8 Wk, 65C, 50/50, New, Mx LR, 23/50 BI, WRFL

End of test: 2 weeks in oven at 65C

Finding: SwBlister: Blister on sidewall, PCD: Ply Coat Delamination

N2122 – G2 PJ0RY5HV3305 LT235/85R16

Test: HYB8_65_II_BI_23_R Oven 8 Wk, 65C, 50/50, New, Mx LR, 23/50 BI, WRFL
End of Test: 1 week @ 65C
Finding: SwBlister: Blister on sidewall, PCD-TC: Ply Coat Delamination To Cords
Perforated liner found where sidewall blowout occurred. Separation of turn-up to body ply and sidewall and loss of adhesion to the cords. Skim rubber removed from the body cords.



N2125 – G2 PJ0RY5HV3305 LT235/85R16
Test: HYB8_65_II_BI_23_R Oven 8 Wk, 65C, 50/50, New
End of test: 3rd week oven 60C
Finding: Bead blowout
No image available.

N2134 - R2 XLW8E4231603 LT265/75R16
Test: HYB8_65_II_BI_23_R Oven 8 Wk, 65C, 50/50, New, Mx LR, 23/50 BI, WRFL
End of Test: 7 Weeks in oven at 65C
Finding: SwBlister: Blister on sidewall

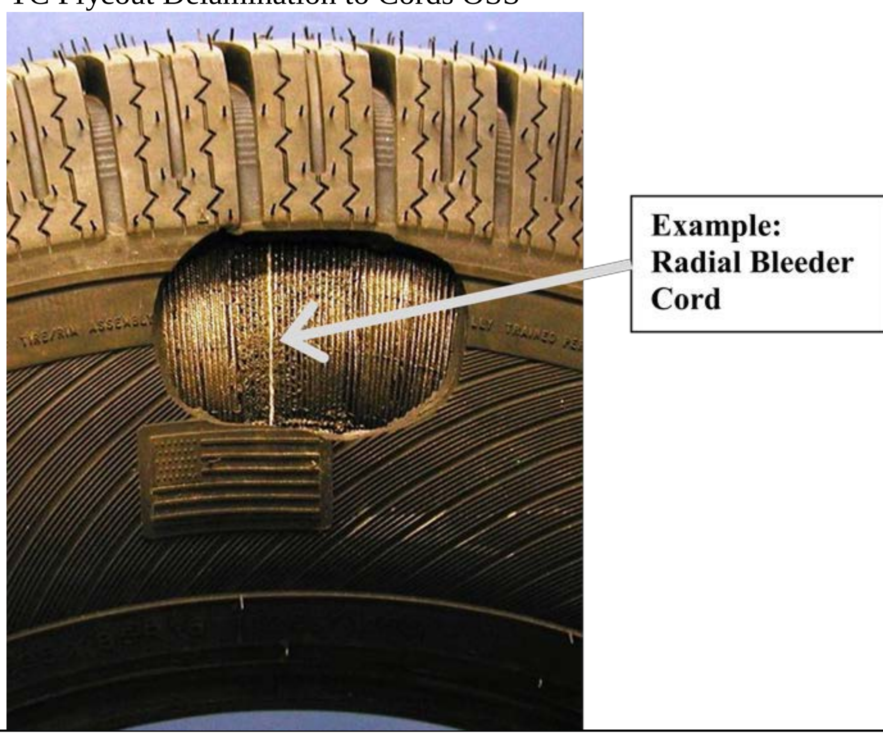
N2137 - R2 XLW8E4231604 LT265/75R16
Test: HYB7_60_II_R Oven 8 Wk, 60C, 50/50, New, Mx LR, 23/50 BI, WRFL
End of Test: 7 Weeks in oven at 60C
Finding: Blister on tread

N2208 - B4 ENLFDAC5204 LT285/75R16
Test: HYB7_60_II_R Oven 7 Wk, 60C, 50/50, New, Mx LR
End of test: 6th week oven 65C
Finding: PCD- SwBlister Blister on sidewall OSS White sidewall
Sidewall separations between the turn-up and filler and turn-up and white sidewall.

Some slight inclusions were found in the liner, but no perforation was found.
Bead area had damage apparently caused during dismounting.

N2329 – O1   PJORH6LV3305   LT235/85R16
Test: HYB8_65_II_R oven age at 65C
End of Test: 5 weeks in oven at 65C
Finding: PCD-I SS

N2332 - O1   PJORH6LV3305   LT235/85R16
Test: HYB8_65_II_R oven age at 65C
End of Test: 3 weeks in oven at 65C
Finding: PCD-TC Plycoat Delamination to Cords OSS



N2334 – O1 PJORH6LV3305   LT235/85R16
Test: HYB8_65_II_BI_23_R Oven 8 Wk, 65C, 50/50, New, Mx LR, 23/50 BI, WRFL
End of Test: 2 weeks @ 65C Bead
Finding: SwBlister: Blister on sidewall, PCD-TC: Ply Coat Delamination To Cords

Perforated liner found where sidewall blowout occurred. Separation of turn-up to body ply and sidewall and loss of adhesion to the cords. Skim rubber removed from the body cords.

N2346 – O2 PJW8JLLV3405 LT265/75R16

Test: HYB8_65_II_R oven age at 65C

End of Test: 3 weeks in oven at 65C

Finding: PCD-I Ply Coat Delamination Interface SS


678
N2346 – O2 PJW8JLLV3305 LT265/75R16
Test: HYB8_65_II_R oven age at 65C
End of Test: 3 weeks in oven at 65C
Finding: SwBlister Sidewall blister starting at turnup ends

N2349 – O2 PJW8JLLV3405 LT265/75R16
Test: HYB7_60_II_R oven age at 60C
End of Test: 6 weeks in oven at 60C
Finding: Cracks in Bead Filler

N2381 – D3 U9URTT91405 P205/65R15
Test: HYB8_65_II_R oven age at 65C
End of Test: 4 weeks in oven at 65C
Finding: Shoulder sep
No image available

N2409 -D5 UPW8XDJ2405 LT265/75R16
Test: HYB8_65_II_R oven age at 65C
End of Test: 5 weeks in oven at 65C

Finding: PT+B2D: Partial tread and Belt 2 Detachment
Found tread partially blown off in oven.

N2410 – D5 UPW8XDJ2105 LT265/75R16
Test: HYB8_65_II_R oven age at 65C
End of Test: 5 weeks in oven at 65C
Finding: BES; PCD-I OSS / RWL

N2413 – D5 UPW8XDJ0805 LT265/75R16

Test: HYB8_65_II_BI_23_R Oven 8 Wk, 65C, 50/50, New, Mx LR, 23/50 BI, WRFL

End of Test: 6 weeks oven at 65C

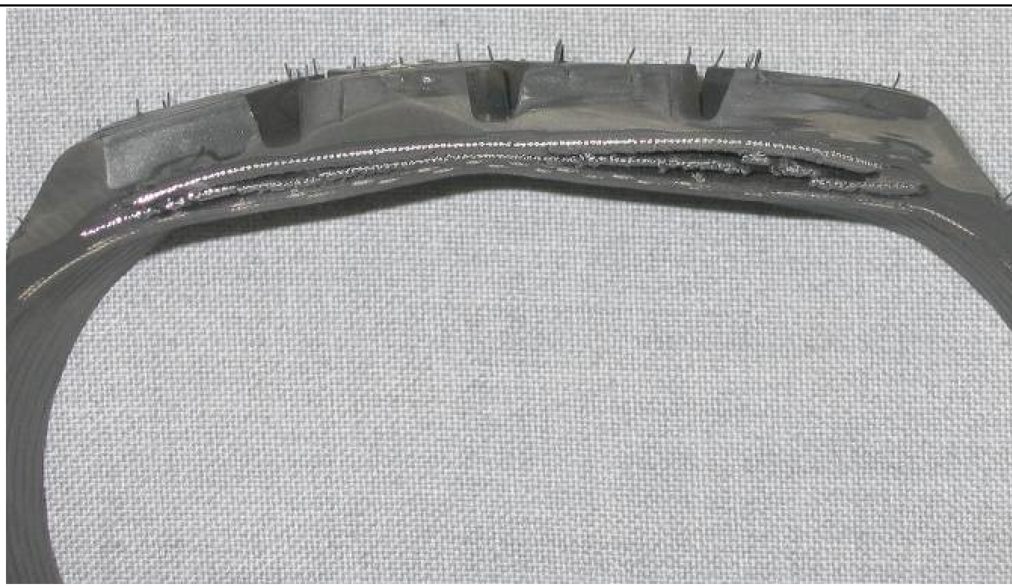
Finding: TGCr, B1P1D, BBS

Tire was found with what appeared to be large liner separation which appears to have allowed air to flow to the belt edges and cause severe cracking at the belt edges.

TGCr - Tread Groove Cracking

OSS side of tire has cracks nearly 340 to 350 degrees (see area highlighted with white line).

After sectioning B1P1D (belt to carcass detachment or separation) and BBS (belt-to-belt separation) found after sectioning. See section below.



N2415 – D5 UPW8XDJ2105 LT265/75R16
Test: HYB7_60_II_R oven age at 60C
End of Test: 7 Weeks in oven at 60C
Finding: Tread Blister
No image available.

APPENDIX 3. TIRES AND TESTS USED IN PHASE 3 ROADWHEEL TESTING

Tire Type	Temperature, °C	Time in Oven, week	Pre-Oven Roadwheel Break-in (# hrs and km/h)	Barcode	DOT TIN Number
B4	New			2201	EJLFDAC4704
	65	5	None	2202 2203	ENLFDAC5204 ENFLDAC5204
	65	5	None	2206 2207	ENFLDAC5204 ENFLDAC5204
	60	7	None	2209	EJLFDAC5104
				2210	EJLFDAC5104
B 6	New			2214	7X9LPDW5204
				2215	7X9LPDW1905
	65	5	None	2216	7X9LPDW1905
				2217	7X9LPDW1905
	65	5	23/50	2219	7X9LPDW1905
	60	7	None	2223	7X9LPDW3205
				2224	7X9LPDW3205
B 7	New			2228	VN73WM04804
	65	5	None	2229	VN73WM04804
				2230	VN73WM04804
	65	5	23/50	2232	VN73WM04804
				2233	VN73WM00105
	60	7	None	2235	VN73WM00105
				2236	VN73WM00105
C3	New			2445	A30846JB1505
				2446	A30846JB1505
	65	5	None	2447	A30846JB1505
				2448	A30846JB1505
	65	5	23/50	2450	A30846JB1505
				2451	A30846JB1505
	60	7	None	2453	A30846JB1505
				2454	A30846JB1505
C5	New			2483	ACUR3K43405
				2484	ACUR3K43405
	65	5	None	2485	ACUR3K41905
				2486	ACUR3K42005
	65	5	23/50	2489	ACUR3K42005
				2490	ACUR3K42005
	60	7	None	2492	ACUR3K42005
				2493	ACUR3K42005

Tire Type	Temperature, °C	Time in Oven, week	Pre-Oven Roadwheel Break-in (# hrs and km/h)	Barcode	DOT TIN Number
D2	New			2366	PJC6XTLR2805
				2367	PJC6XTLR2505
	65	5	None	2368	PJC6XTLR2405
				2369	PJC6XTLR2505
	65	5	23/50	2372	PJC6XTLR2905
				2373	PJC6XTLR2905
	60	7	None	2375	PJC6XTLR2505
				2376	PJC6XTLR2405
D3	New			2379	U9URTT93105
				2380	U9URTT93105
	65	5	None	2381*	U9URTT91405
	65	5	23/50	2384	U9URTT93105
				2385	U9URTT93105
D4	New			2418	3DYUB8W1505
				2419	3DYUB8W1505
	65	5	None	2420	3DYUB8W1505
				2421	3DYUB8W1505
	65	5	23/50	2423	3DYUB8W1505
				2424	3DYUB8W1505
	60	7	None	2426	3DYUB8W1505
				2427	3DYUB8W1505
D5	New			2405	UPW8XDJ0105
				2406	UPW8XDJ2205
	65	5	None	2407	UPW8XDJ2205
				2408	UPW8XDJ2305
	65	5	23/50	2410*	UPW8XDJ2105
				2411	UPW8XDJ0805
	60	7	None	2414	UPW8XDJ0805
				2415*	UPW8XDJ2105
G 2	New			2114	PJ0RY5HV3205
				2116	PJ0RY5HV3205
	65	5	None	2118*	PJ0RY5HV3205
	65	5	23/50	2120*	PJ0RY5HV3205
				2121	PJ0RY5HV2705
	60	7	None	2123	PJ0RY5HV3305
				2124	PJ0RY5HV3305
O1	New			2327	PJ0RH6LV3305
				2328	PJ0RH6LV3305
	65	5	None	2329*	PJ0RH6LV3305
				2330	PJ0RH6LV3305
	65	5	23/50	2332*	PJ0RH6LV3305
				2333	PJ0RH6LV3305
	60	7	None	2335	PJ0RH6LV3305
				2336	PJ0RH6LV3305

Tire Type	Temperature, °C	Time in Oven, weeks	Pre-Oven Roadwheel Break-in (# hrs and	Barcode	DOT TIN Number
O2	New			2340	PJW8JLLV3405
				2341	PJW8JLLV3405
	65	5	None	2342	PJW8JLLV3405
				2343	PJW8JLLV3405
	65	5	23/50	2346*	PJW8JLLV3405
				2347	PJW8JLLV3405
	60	7	None	2340	PJW8JLLV3405
				2349*	PJW8JLLV3405
				2350	PJW8JLLV3405
O3	New			2314	UPURTX33305
				2315	UPURTX33305
	65	5	None	2316	UPURTX33305
	65	5	23/50	2319	UPURTX33305
				2320	UPURTX33205
	60	7	None	2323	UPURTX33305
O5	New			2301	U9C6HTE3305
				2302	U9C6HTE3305
	65	5	None	2303	U9C6HTE3305
				2304	U9C6HTE3305
	65	5	23/50	2306	U9C6HTE3305
				2307	U9C6HTE3305
	60	7	None	2309	U9C6HTE3305
				2310	U9C6HTE3305
P1	New			2001	UT73B9J2805
				2002	UT73B9J2805
	65	5	None	2003	UT73B9J2805
				2004	UT73B9J2705
	65	5	23/50	2006	UT73B9J0305
				2007	UT73B9J2705
	60	7	None	2010	UT73B9J2705
P2	New			2027	UP0RPAL2005
				2029	UP0RPAL2005
	65	5	None	2030	UP0RPAL2005
				2031	UP0RPAL2005
	65	5	23/50	2033	UP0RPAL2005
				2034	UP0RPAL2005
	60	7	None	2036	UP0RPAL2005
				2037	UP0RPAL2005

Tire Type	Temperature, °C	Time in Oven, week	Pre-Oven Roadwheel Break-in (# hrs and km/h)	Barcode	DOT TIN Number
P3	New			2014	UTHLPAN3205
				2015	UTHLPAN3205
				2053	UTHLPAN2806
				2054	UTHLPAN2806
	65	5	None	2016	UTHLPAN3205
				2017	UTHLPAN3205
				2057	UTHLPAN2806
				2058	UTHLPAN2806
	65	5	23/50	2020	UTHLPAN3205
				2021	UTHLPAN3205
	60	7	None	2023	UTHLPAN3205
				2024	UTHLPAN3205
R2	New			2127	XLW8E4231203
				2128	XLW8E4231203
	65	5	None	2129	XLW8E4231403
				2130	XLW8E4231503
	65	5	23/50	2132	XLW8E4231603
				2133	XLW8E4231603
	60	7	None	2137*	XLW8E4231604
				2138	XLW8E4231604
T2	New			2664	9TKU93A0706
				2665	9TKU93A0706
	65	5	None	2668	9TKU93A0706
				2669	9TKU93A0706
U2	New			2078	EUFC3TMR4705
				2079	EUFC3TMR4705
	65	5	None	2082	EUFC3TMR4705
				2083	EUFC3TMR4705

*Failed during oven aging and could not be tested for roadwheel endurance.

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May 2013

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9364-050613-v2